THE PROPERTIES OF UNDERWATER WELDED MILD STEEL AND HIGH STRENGTH STEEL JOINTS.

Michael Bruce Meloney

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Submitted in partial fulfillment of the requirements for the degree of Ocean Engineer and the Degree of Master of Science in Naval Architecture and Marine Engineering at the Massachusetts Institute of Technology, June, 1973.

ABSTRACT

This thesis is divided into two parts, the first being an investigation into the multipass underwater welding of mild steel, and the second an investigation into the feasibility of underwater welding HY-80 steel. With the former, current underwater shielded metal-arc welding technology was employed, while with the latter, current shielded metal-arc air welding technology was adapted to underwater welding.

Multipass underwater mild steel welds are very often required and are commonly employed during underwater repair and salvage operations. However the physics, and even the basic properties of multipass welding are not well known. Experimental results showed that multipass underwater butt welds can be fabricated with marginally satisfactory tensile and impact strength. It appears that weld metal embrittlement due to rapid quenching causes the weld metal to become most susceptible to brittle fracture. This is significantly different from air welding, where the heat affected zone is more susceptible to brittle fracture.

There are presently a substantial number of naval vessals afloat with all or part of their hull structure fabricated with HY-80 steel. However no investigation has been made into the feasibility of welding HY-80 underwater in order to perform voyage repairs or carry out salvage operations. Simple lap and tee joints were fabricated underwater from HY-80 steel of various thicknesses, and tests conducted to determine joint strength and ductility as well as overall weld quality. Both single and multipass joints were fabricated. It was found that acceptable joints could be fabricated, with joint performance comparable to that of underwater welded mild steel joints.

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Title: Professor of Ocean Engineering

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CHAPTER I - INTRODUCTION

This report is divided into two parts, the first being an investigation into the multipass underwater welding of mild steel, and the second an investigation into the feasibility of underwater welding HY-80 steel. With the former, current underwater shielded metal-arc welding technology was employed, while with the latter current shielded metal-arc air welding technology was adapted to underwater welding.

Shielded metal-arc underwater welding has been the most studied underwater welding process to date, however the depth of knowledge of this process is still superficial. The shielded metal-arc process has proven satisfactory for the underwater repair and salvage of ships since World War II, but now industry needs the capability to fabricate steel structures underwater, as well as maintain them. Tremendous savings could be made if undersea pipelines, offshore oil towers and other ocean structures could be fabricated in place by a wet welding process. This current commercial need has spurred great interest not only in developing such a wet welding process, but in understanding the physical processes and phenomena of underwater welding in general.

Part one of this report evaluates some of the properties of multipass shielded metal-arc underwater welds. Multipass

welds are very often recommended[1] or required during underwater repair welding due to poor joint fit-up, thick plating, etc., and are therefore commonly employed actual underwater repair and salvage operations. However the physics, and even the basic properties of multipass welding are not well known. Grubbs[2] in 1971 reported success by the Chicago Bridge and Iron Company in producing sound multipass underwater SMA welds but this was the only reference found which investigated any aspect of multipass welding.

Part two of this report was an initial investigation into the feasibility of welding HY-80 steel joints underwater. The U.S. Navy has almost two decades of experience in the air welding of HY-80 plate for submarine hulls. Its large strength to weight ratio, plus good weldability under controlled conditions makes HY-80 steel an obvious choice as a surface ship hull material. There are presently a substantial number of naval vessels afloat with all or part of their hull structure fabricated with HY-80 steel. Their exceptional performance will increase the use of this material in future ship construction.

A literature survey revealed no published record of any experimental or theoretical work done on the underwater

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[1]See Navy Underwater Cutting and Welding Manual pp 6-12 to 6-15.

[2]Grubbs op. cit.

welding of <u>any</u> high strength steel. Verbal conversations with the Naval Ships Systems Command welding engineer, and the Office of the Supervisor of Salvage confirmed that no U.S. Navy "in house" or contract study was presently going on, or was planned on the underwater welding of HY-80 steel. The concensus of opinion was that a high strength quenched and tempered steel such as HY-80 could not be satisfactorily welded underwater.

It seems prudent at this time to conduct an initial investigation into the actual underwater weldability of HY-80 steel for the purpose of performing emergency underwater repairs or conducting salvage operations, through the use of a wet fusion welding process. The main thrust of this study was to determine the practical limits of joint strength and ductility, as well as the overall weld quality which is achievable in the underwater welding of HY-80 steel.

CHAPTER II- UNDERWATER WELDING OF MILD STEEL PLATE

Section A - Procedure

A1. Introduction

The purpose of this portion of the investigation was twofold. First to gain practical experience in the "art" of underwater welding under controlled laboratory conditions in order to fabricate actual fillet weld lap and tee joints underwater from HY-80 steel plate. Second to determine the tensile strength and notch toughness of multipass underwater welded butt joints and compare these values to bead-on-plate specimens and base plate properties.

A2. Underwater Welding Procedures

Welding Equipment. The welding equipment and arrangement shown in figure 1 was used for the underwater welding of both mild steel and HY-80 steel specimens, and consisted of the following:

1. water tank
2. power source with standard electrode holder
3. current, voltage, and time recorders

Water Tank. The welding experiments were conducted in a steel tank measuring four feet long by three feet high by two feet wide. The exterior of the tank was sheathed in wood and rubber matting to prevent electrical shocks. A platform, containing clamps for securing the specimen, was fitted to the inside of the tank. The platform was located

EQUIPMENT SCHEMATIC

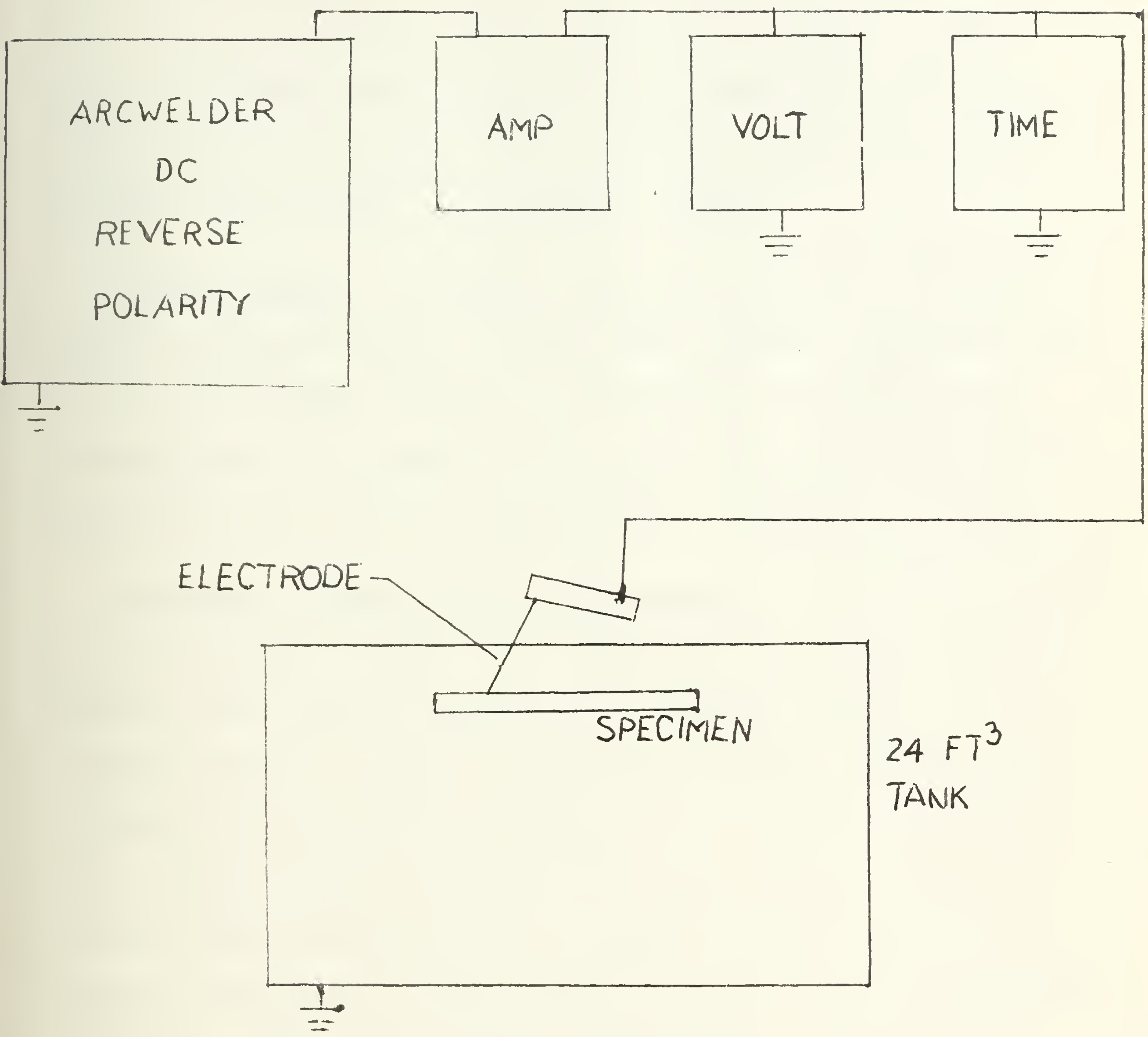


FIGURE 1

one foot from the top of the tank so that the electrode, but not the electrode holder, would be submerged in the water. The tank was filled by a line supplying ordinary tap water (Boston, Mass.) and drained by gravity discharge. The tank was grounded to the power source.

Power Source. A Lincoln Idealarc Model R3M 400 amp D.C. welding machine was used as the power source. DCRP was used in all experiments because of the ease in initiating and maintaining an arc, and the less dense flux cloud produced during welding, with no apparent loss in weld penetration.

Current, Voltage and Time Recorders. A General Electric D-C (0.400 amp.), Model 10H, recording ammeter was used to measure the current flowing in the welding circuit. An Esterline Angus (0.100 V) recording voltmeter was selected to measure the operating voltage during welding. A timing device consisting of a General Time Co., Model 320-1, electric clock connected to a circuit breaker was used to measure the amount of time required to lay a given length of weld bead. When the arc was initiated the breaker would close and start the clock; breaking the arc would cause the clock to stop. Dividing the length of the bead by the elapsed time gave the electrode travel speed.

Welding Criteria. MIL-STD-00418B (SHIPS)- Mechanical Tests For Welded Joints was used as a standard in the preparation, welding, cutting, and testing of tensile and Charpy

impact specimens.

Welding Materials. Cold rolled mild steel plate (ASTM 242) was utilized for both bead-on-plate and butt joint specimens. Tensile specimens were cut from 10" long by 6" wide by 3/16" thick welded plates. Charpy impact specimens were cut from 4" long by 4" wide by 3/4" thick welded plates. 5/32" E6013 electrodes, coated with parrafin prior to welding, were used for all mild steel underwater welds.

Welding of ¼" Mild Steel Tensile Specimens. 10"L x 6"W plates were received in a cleaned and surface primed condition. For transverse bead-on-plate welds the weld would be made accross the width of the plate, and then a number of 10" long specimens cut from the plate. For longitudinal bead-on-plate welds, three 10" x 2" strips were machine cut from each 10" x 6" plate prior to welding. For transverse butt joint specimens, each 10" x 6" plate was cut in half accross the width so that two 5"L x 6"W plates could be butt welded to the original 10" x 6" size, and then cut to proper specimen sizes.

The regions to be welded on each plate were sanded and wire brushed to remove primer paint and expose clean metal along the desired weld line. The plates were then clamped to the water tank welding tray and manually welded in 8" of fresh water. Bead-on-plate welds were single pass. The ungrooved butt joints were multipass, with two full passes

made on both sides of the plates. Due to the excessive turbidity which evolves during underwater welding it was necessary to use a wooden straightedge as an electrode guide in order to lay down a straight weld bead along the desired weld line. The straightedge was easily clamped to the side of the welding tray, and greatly facilitated the manual welding of all the specimens.

After completing the transverse welds, 1" was cut off each long side of the plate and discarded in order to eliminate any edge effects in the test specimens. The remaining 10" x 4" welded plate was then cut into two 10" x 2" pieces and machined as shown in figure 2A.

The longitudinally welded plates were already cut to proper size and machined as shown in figure 2B. Plate edge effects were not significant in this case. After machining, the weld reinforcement was ground off, but care was taken not to eliminate weld undercut.

Welding of 3/4" Mild Steel Charpy Impact Specimens. Two 4" x 4" x 3/4" plates were prepared and butt welded in the same manner as the ½" transverse butt joints. Numerous multipass welds were made in the ungrooved joint in order to completely fill the joint. All passes were made on one side with hand clamps preventing angular distortion of the component plates. Each pass was hand wire brushed immediately after welding, and after each second pass the entire unit was removed from the tank and machine wire brushed to remove all

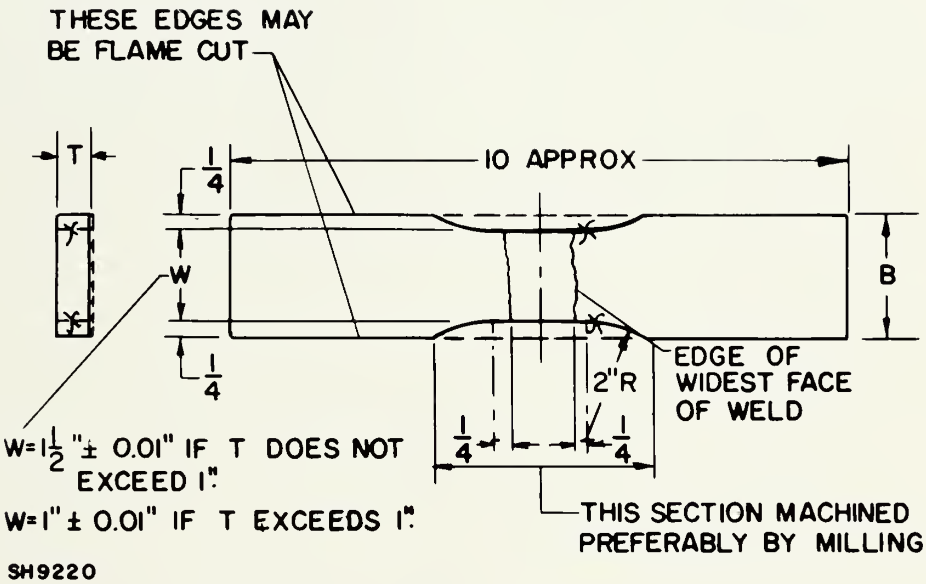
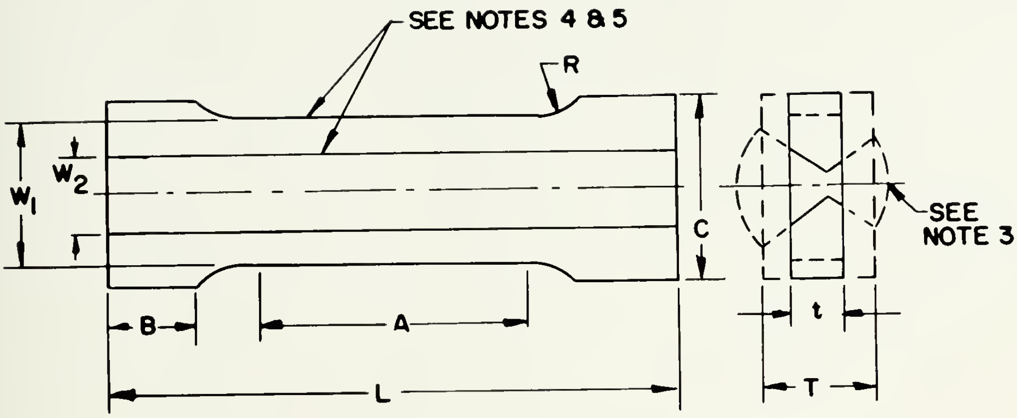


Figure 2A - Transverse tensile specimen.



SH9222

	DIMENSIONS	
	1	2
W_1 - Width at center (note 5)	1±1/16 inch	1-1/2±1/8 inch
W_2 - Width of weld (note 4)	1/2 W_1 (approx.)	1/2 W_1 (approx.)
T - Thickness (note 1)	Thickness of material	
t - Thickness (note 2)	Thickness of specimen	
R - Radius of fillet	1 inch, minimum	1 inch, minimum
L - Overall length	10 inch, minimum	10 inch, minimum
A - Length of reduced section	2-1/4 inch, minimum	2-1/4 inch, minimum
B - Length of grip section	3 inch, minimum	3 inch, minimum
C - Width of grip section	1-1/2 inch, approx.	2 inch, approx.

NOTES:

1. The dimension "T" is the thickness of the plate section as provided for in the applicable material specification.
2. The dimension "t" is the thickness of the specimen.
3. The weld reinforcement and backing strip, if any, shall be removed flush with the surface of the specimen.
4. The width "W_2" of the weld may be varied to approximate 1/2 W_1 by selecting an appropriate specimen thickness "t" and its location within the weld.
5. The width "W_1" may be varied within reason to accommodate the approximation of W_2 = 1/2 W_1 if it is not possible to meet the requirements of note 4.
6. The specimen ends shall be symmetrical with the centerline of the reduced section within 0.01 inch.
7. Remove final machining marks on reduced section surfaces with 180 grit abrasive parallel to the longitudinal direction.

Figure 2B - Longitudinal tensile specimen.

the remaining flux covering. The joint gap was approximately two electrode diameters wide, so two full passes could be made side by side without resulting slag entrapment. After completion of the welding, ½" was cut off each weld end and discarded. The weld reinforcement was ground down to the base plate, and then 1/16" was milled off the top side of the entire welded plate. Five Charpy specimens were then cut from the welded butt joint. The specimens were cut perpendicular to the weld bead with the center of the weld bead coinciding with the center of the Charpy specimen. In this way the toughness of the multipass region alone was evaluated.

Welding Parameters. The Navy Underwater Cutting and Welding Manual gives a recommended current range for welding underwater with E6013 electrodes. This was used as a guideline in initial bead-on-plate test runs. Then the range of current settings for given travel speeds was narrowed down and optimized for the steel thickness being welded.

The range of welding parameters used were as follows:

1/4" mild steel plate	
Current	190-205 Amps (DCRP)
Voltage	28-33 Volts
Travel speed	11.7 - 14.5 inches/min.
Ambient temp.	39.6°F

3/4" mild steel plate	
Current	210-230 Amps (DCRP)
Voltage	21-27 Volts
Travel speed	9.5-11.4 inches/min.
Ambient temp.	41°F

Section B - Experimental Results

Tensile tests and Charpy impact tests were conducted in accordance with MIL-STD-00418B Mechanical Tests For Welded Joints.

Tensile tests were conducted on a Baldwin hydraulic testing machine. The maximum load to failure and the fracture location were recorded, and the reduction in area and elongation measured for each specimen. Tensile strength was computed as the maximum load to failure divided by original cross-sectional area. Test results are shown in Table 1.

Charpy impact specimens were fractured on a Tinius Olsen Universal Impact Machine. Three test temperatures were used, (68°F, 32°F, and -60°F) with three specimens fractured at each temperature. Test results are shown in Table 2.

Table 1 - Results of Mild Steel Tensile Tests

Specimen	Tensile Strength (psi)	% Elong. in 2 in.	% Reduction in Area	Fracture Location*
1A	65,610	9.4	12.0	W.M.
1B	60,370	7.8	11.1	W.M.
1C	64,000	9.3	12.0	W.M.
1D	66,200	9.3	11.9	W.M.
1E	54,825	12.5	11.0	W.M.
Ave Series 1	62,200	9.7	11.6	----
2A	72,210	26.9	19.3	B.M.
2B	68,925	24.2	23.4	B.M.
2C	64,710	15.9	24.5	HAZ
2D	52,840	11.9	16.3	W.M.
2E	55,140	13.0	14.6	W.M.
Ave Series 2	62,765	18.4	19.6	----
3A	49,333	6.3	9.7	W.M.
3B	51,200	9.7	11.3	W.M.
3C	27,570	3.6	6.1	W.M.
3D	43,285	7.4	9.2	W.M.
Ave Series 3	42,847	6.8	9.1	----

* W.M. = Weld Metal
HAZ = Heat Affected Zone
B.M. = Base Metal

Series 1 = Single pass longitudinal bead-on-plate.

Series 2 = Single pass transverse bead-on-plate.

Series 3 = Multipass transverse butt weld.

Table 2 - Results of Multipass Mild Steel Charpy Impact Tests

Specimen	Temperature (^{o}F)	Impact Energy (ft-lbs.)
4A	$68^{o}F$	28.0
4B	$68^{o}F$	28.2
4C	$68^{o}F$	26.1
Ave	$68^{o}F$	27.4
4D	$32^{o}F$	20.0
4E	$32^{o}F$	13.5
4F	$32^{o}F$	11.7
Ave	$32^{o}F$	15.1
4G	$-60^{o}F$	7.6
4H	$-60^{o}F$	6.4
4I	$-60^{o}F$	8.0
Ave	$-60^{o}F$	7.3

Section C - Discussion of Results

C1. Bead-on-Plate Tensile Tests

Weld penetration in the longitudinal and transverse bead-on-plate specimens extended down to about two-thirds the plate thickness. However even with this deep penetration, specimen behavior during testing approached that of unwelded base plate rather than that of welded butt joints.

Transverse bead-on-plate specimens showed the best strength and ductility of the three specimens tested. This is surprising in view of the fact that these specimens were loaded in a direction perpendicular to weld undercut, and therefore undercut notch effects should have caused premature failure. Instead these specimens performed significantly better than the longitudinal bead-on-plate welds which were loaded in parallel to weld undercut notches, and thus failed by a means other than root crack initiation and propagation.

In the longitudinal weld specimens, all zones of the weld strain equally and simultaneously. The region with the poorest ductility will therefore initiate fracture below the ultimate tensile strength of the surrounding base metal. All fractures in these specimens initiated in the weld metal bead. The conclusion then is that for underwater welded mild steel, weld metal embrittlement rather than weld undercut will initiate premature, catastrophic failure.

C2. Butt Joint Tensile Tests

Comparison of butt weld test results to bead-on-plate

test results indicates that bead-on-plate specimens do not simulate actual butt joint behavior very well. No matter how deep the bead-on-plate weld penetration may be, there will still be some base metal below the weld bead which will significantly alter test results.

Transverse multipass butt joints had 68% the tensile strength and only 42% the ductility of the transverse bead-on-plate specimens, whereas the bead-on-plate specimens had 95.2% the tensile strength and 74% the ductility of ASTM 242 base plate. In addition the butt joints all failed through the weld metal, as predicted by the longitudinal specimen test results, while the transverse bead-on-plate specimens failed in all three regions without preference.

Series 3 results correlate very well with the work of Grubbs[3] who also tested the tensile and impact properties of multipass underwater welded mild steel. This leads to the conclusion that the extensive bead-on-plate underwater welding investigation carried out by Silva[4] does not give a good indication of actual underwater welded joint performance.

C3. Charpy Tests

Results of impact tests show that the multipas underwater welds met the minimum Charpy impact values for marine steels (i.e. 10-15 ft-lb minimum at 32°F).[5] The brittle fracture

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[3] Grubbs op. cit.

[4] Silva op. cit.

[5] Cohen op. cit. pp1

transition temperature is just about at 32°F which makes the welds barely satisfactory for use in the coldest ocean water regions.

Again Charpy impact test results correlate well with the work of Grubbs.* except for the higher value at 30°F which indicates a significantly lower transition temperature (about 0° F) for his welds.

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*Multipass underwater weld Charpy impact values were:

24 ft-lb at 70°F

22 ft-lb at 30°F

10 ft-lb at -30°F

Section D - Conclusions and Recommendations on the Underwater Welding of Mild Steel

D1. Conclusions

a. Satisfactory multipass underwater welded butt joints can be fabricated. However joint strength could be significantly improved by increasing weld metal and heat affected zone ductility, and decreasing weld undercut. Weld zone ductility can be increased by reducing the severe quenching effect of the aqueous environment and thereby improving weld zone microstructure. Undercut can be reduced through improved welding technique and optimization of welding parameters.

Improving weld zone grain structure will also increase joint notch toughness.

b. Porosity was not a significant problem either in single pass bead-on-plate welds or in multipass butt joints.

c. Bead-on-plate tensile specimens indicated the weakest regions in the underwater weld zone (i.e. weld metal, and undercut notch root) where premature fracture is most likely to occur. However bead-on-plate specimens did not give a valid indication of actual butt joint performance.

d. Excessive turbidity created in the water during welding made proper placing of the bead extremely difficult,

especially in the welding of thin plate butt joints where a close fit up leaves no groove to guide the electrode along the desired weld line. In multipass welding, a wider joint gap can be used which provides better guidance for the welder.

D2. Recommendations

a. There is a need to investigate the performance of underwater welded joints which are welded in the vertical and overhead positions. All literature references cited in this report, except Grubbs, investigated the quality of underwater welds made in the horizontal position only. This makes laboratory work easier, but is highly restrictive in the applicability of test results to actual underwater welding, where most welding is done in positions other than horizontal. In fact, most operational welding is done on curved surfaces (i.e. ship hulls, pipelines, etc.) where the welding position is continually changing. The weldability of such curved joints may vary with welding position.

b. Use of a welding shroud to reduce the quenching effect of the water environment has been shown to be beneficial by Silva[6]. Further study on the effects and design of

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[6]Silva, op. cit. pp 40-75

welding shrouds for all position welding is needed.

c. The possibility of tempering the most brittle regions of the underwater weld zone needs to be investigated. Oxy-hydrogen and Oxy-MAPP torches, or Burning Bars could be used for this purpose. Research and development of effective tempering techniques for underwater welds will bring the highest return in increased joint performance per dollar invested.

d. Further investigation on the best combinations of welding parameters and welding technique for minimizing weld undercut is needed. Simple shrouds can be used to reduce undercut in the horizontal welding position, but will not be effective in vertical and overhead shielded metal arc welding. Optimization of welding parameters and techniques will be effective in reducing undercut in all welding positions.

CHAPTER III- UNDERWATER WELDING OF HY-80 STEEL

Section A - Procedure

A1. Introduction

The purpose of this investigation was to determine the feasibility of welding HY-80 steel plate underwater in order to fabricate joints of reasonable quality and strength for temporary repairs such as interim (voyage) repairs or for use during salvage operations. The general approach taken was to compare specific properties of simple underwater welded joints with the same joint configuration welded in air. Joints were fabricated and specimens prepared and tested in accordance with Department of Defense MIL-STD-00418B Mechanical Tests for Welded Joints and with MIL-S-16216H Fabrication, Welding and Inspection of HY-80 Submarine Hulls.

Fillet-weld lap joints, tee-bend joints and tee-tensile joints were fabricated with ½" HY-80 plate in air and underwater, and the specimens tested and compared. Also 3/4" tee-bend joints and tee-tensile joints were fabricated underwater, with specimens cut and tested. Randomly selected air and underwater welded specimens were metallographically examined and microhardness tested to better determine the overall weldability and weld quality of the underwater welded joints compared to air-welded HY-80 plate.

The same welding equipment and set-up used for the underwater welding of mild steel was used for the underwater

welding of the HY-80 steel. The HY-80 air welds were performed on a welding workstand using the same power source. 1/4" and 3/4" rolled HY-80 plate and 1/8" diameter E11018 and E310-16 electrodes, heated in holding ovens for a minimum of four hours, were utilized. Both electrodes were hand coated with a thin coat of paraffin after cooling and prior to welding.

Determination of Welding Parameters. Since no references exist which give recommended welding parameters for the underwater welding of HY-80 steel, a trial and error method was employed with underwater bead-on-plate welds to obtain a range of values suitable for the plate thickness and electrode diameter being used. For the Lincoln Idealarc Model R3M 400 D.C. welding machine there is no separate voltage setting. Voltage is preset in the machine to vary proportionally, with current, as the current setting is adjusted. Therefore as a first cut the range of values determined were current setting required to initiate and maintain an arc, utilizing the drag welding technique (lower limit), and current setting which caused burnthrough (upper limit) using a 1/8" diameter E11018 electrode. Practice runs were then made with actual fillet-weld lap joints and tee joints in order to firstly accustom the author to "feel" the joint and place the weld bead along the desired line even with excessive turbidity, and secondly to narrow down the range of welding variables, in this case current and travel speed,

so as to maximize joint penetration while minimizing weld undercut. In all cases the maximum heat input was well below the maximum allowable heat input for 1/4" and 3/4" HY-80 plate listed in appendix A.

A2. Welding of 1/4" HY-80 Fillet Weld Shear Specimens

Transverse fillet shear specimens were cut from welded plates as shown in figure 3. The component plates were received in a cleaned and surface primed condition. The plates were cut to size and the joint areas were pneumatically sanded and machine wire brushed to remove all primer paint and expose clean base metal. The component plates were then assembled in position in the water tank welding tray and the assembly clamped to the welding tray with two large hand clamps. The tank was then filled with fresh water to a level 8 inches above the top plate of assembly and welds were made with 1/8" E11018 electrodes.

Welding Sequence. The sequence of welding was one pass on each of the two top lap joints, then the assembly was turned over and reclamped, and one pass was made on each of the remaining two lap joints. After each pass the weld bead was manually wire brushed to remove the soft, powdery flux covering, which was similar in nature to the quality of the mild steel (E6013) flux covering described in section II A1 . On multipass welds the welded assembly was removed from the tank after the first set of passes was completed and extensively machine wire brushed to remove pockets of

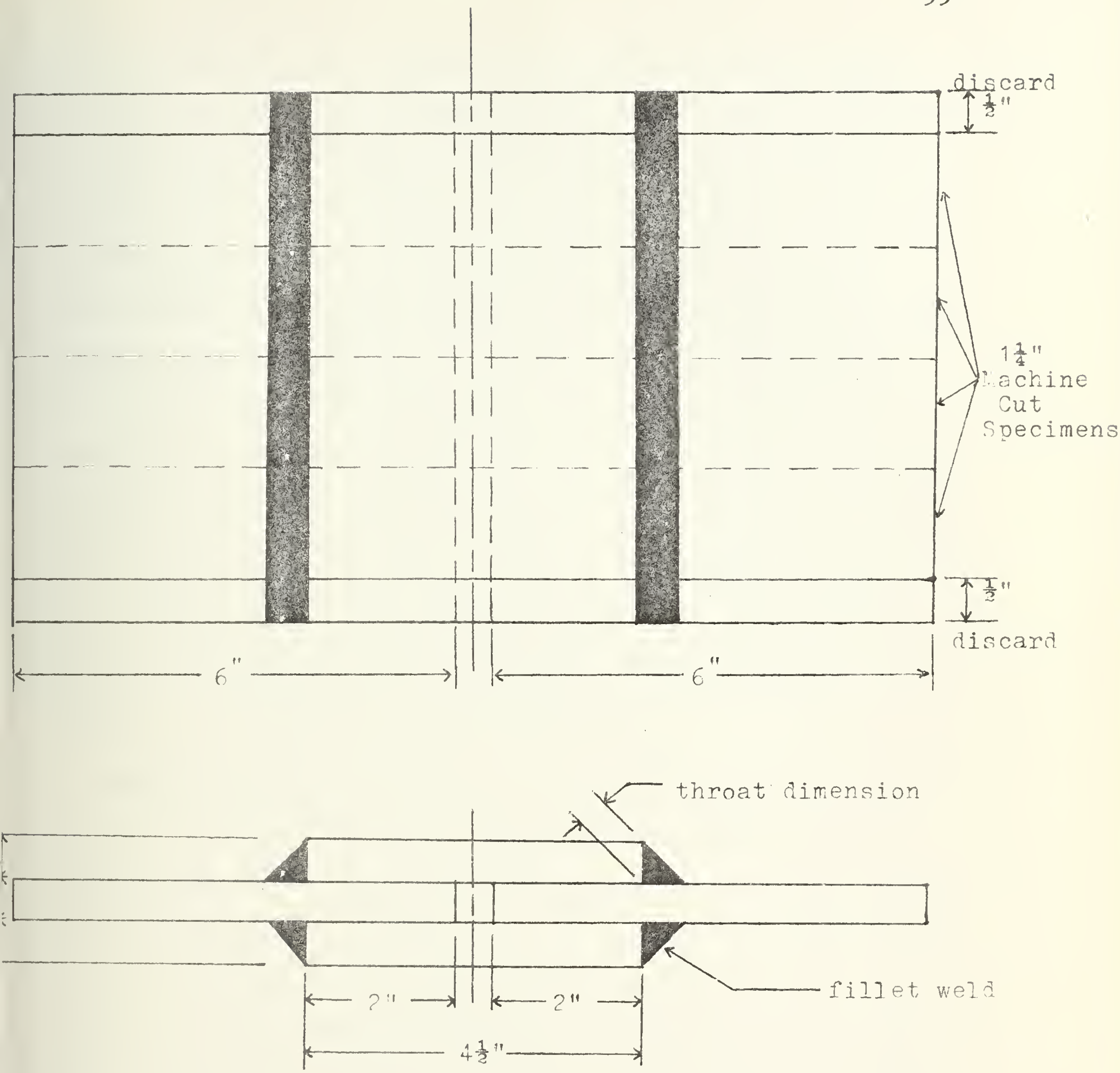

Figure [illegible] - Transverse fillet-weld shear specimen.

flux entrapped in the undercut roots or in surface pores. The assembly was then returned to the water tank, placed on the welding tray unclamped and welded in reverse sequence from the first set of welds, i.e. the joint last welded on the first pass was the first joint welded on the second pass, and so on. This procedure plus the constraining force of the clamps effectively eliminated weld distortion and plate separation. The clamping method was preferred over tack welding because a tack weld would have caused some slag entrapment under the covering plates along the joint which could adversely effect weld fusion in the region of the tack weld. Also a tack weld would have caused local metallographic perturbations which would have unnecessarily complicated an already complex problem.

Surface Defects. Two full passes per lap joint were made in the multipass welds. However the amount and size of surface porosity caused by the second pass was many times worse than that of a single pass. Even making a single pass, and then delaying the placement of the second pass for up to 48 hours did not appreciably decrease the surface porosity problem caused by hydrogen entrapment and diffusion through the weld metal. Ordinarily surface porosity is considered a second order problem compared to undercut in its effect on weld strength and toughness. However in the case of underwater multipass welding of ¼" HY-80 plate with E11018 electrodes the effects

of surface cavities (and subsurface porosity) could be significant through an inordinately large decrease in weld crossectional area and in allowing the water environment access deep into the weld metal, where accelerated corrosion can occur through the formation of differential aeration cells. This would eventually cause extensive local corrosion through the heat effected zone and into the base metal. This latter problem is especially significant in a marine environment, and therefore weld bead "tightness" is essential in underwater welding.

Repair Welds. Although these shear welds were removed from the water after welding and were to be tested in air, the author considered it essential to determine the extent to which the worst cases of surface porosity could be eliminated. The deepest pores in each bead were ground down to the weld root with a small hand-held pneumatic grinding wheel and then machine wire brushed. The welded assembly was then placed back in the tank and short linear "repair" passes were made over the ground down areas. Usually only one such pass was needed unless the "repair" weld bead was not placed exactly on target, in which case the area was manually wire brushed in the tank and another bead placed over the area. Due to poor visibility present even in 8 inches of water, it was impossible to tell if the bead was placed correctly until after brushing away the flux and waiting about 15 seconds for the water to clear. After

extensive practice the author was able to place these "repair" welds with about 75% accuracy, without producing arc craters in the surrounding sound weld metal. Therefore such local fusion repairs are feasible for large surface defects which inevitably occur in the underwater multipass welding of HY-80. It should be mentioned here however that such large defects requiring this type of extensive repair were fairly uncommon.

Austenitic Stainless Steel Electrodes. Grubbs[7], et al, reported success in reducing hydrogen trapping and cracking problems through the use of austenitic stainless steel electrodes in the underwater multipass welding of high carbon equivalent (CE* > 0.40) structural grade steels. In welding underwater, rapid quenching retards the diffusion rate of hydrogen entrapped in the weldment. Austenitic stainless steel electrodes can often decrease the hydrogen problem by storing large quantities of hydrogen in the weld metal, keeping hydrogen away from the crack sensitive heat affected zone and additionally reducing the porosity problem.

Since ¼" HY-80 has a carbon equivalent of 0.546 (chemical composition varies with thickness), it was decided to attempt the underwater welding of ¼" HY-80 shear fillet weld specimens with a suitable austenitic stainless steel electrode as a

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[7] Grubbs, et al, op. cit.

*$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$

back-up in case for some reason the E11018 electrode welds proved unsatisfactory during testing. Plates were prepared, assembled and welded with 1/8" E310-16 electrodes as previously described for the E11018 electrode welded plates. The E310-16 welds were all two pass welds. The weld beads of both the first and second passes were of excellent quality with minimal undercut and very little surface porosity. The bead was smooth and regular and was very similar in appearance to air welded specimens welded with E11018 electrodes. (See figure 4). No surface grinding or spot repairs of any kind were required. The interesting aspect of underwater welding with E310-16 electrodes was that, although the stainless steel electrodes have a much lower melting point than E11018 electrodes, nearly the same welding current and voltage was required to initiate and maintain the arc. The electrode melted at a much higher rate, and the end portion of the electrode which remained out of the water turned cherry red after about ten seconds of welding. This caused the electrode to bend severely so that it had to be discarded after about 20 seconds of welding. This problem would not occur in operational underwater welding where the entire electrode is immersed, however a high electrode travel speed would still have to be used to avoid excessive bead size and to prevent melting of the top lap plate edges. Opacity of the flux cloud was similar to that of the E11018 electrode, however the flux covering over the weld bead was very powdery and could

Figure 4 - Single pass underwater lap weld with E310-16 electrode (left) verses single pass air lap weld with E11018 electrode (right). Upper left corner of E310-16 weld was ground down to eliminate an arc crater caused by an interruption in the weld bead.

easily be removed by hand rubbing.

Welding Parameters. The range of welding parameters used in the underwater welding of fillet weld shear specimens were as follows:

E11018 electrode

current	180-210 Amps (DCRP)
voltage	28-36 Volts
travel speed	9.8-12.1 inches/min.
heat input	32,132-36,020 Joules/in.
ambient temp.	43.6°F

E310-16 electrode

current	160-180 Amps (DCRP)
voltage	35-39 Volts
travel speed	10.6-13.7 inches/min.
heat input	27,328-35,660 Joules/sec.
ambient temp.	44.1°F

All welds were made in fresh water using the electrode drag technique. Plate assemblies were at ambient water temperature for all single pass and multipass welds (interpass temp. = ambient temp). The same power settings were used for single and multipass welds, with only travel speed being varied.

Joint Inspection. Immediately after welding, the plates were carefully visually examined for surface cracking (i.e. longitudinal, transverse, crater cracking) under a 5X viewing glass. The welded plate was then stored on a laboratory shelf for a minimum of 7 days, then visually

examined again and cut into 1½" specimens on a heavy duty hydraulic band saw. No case of surface cracking (immediate or delayed) was found through visual observation. In addition a dye penetrant test was conducted on a randomly selected plate prior to cutting into specimens. All four E11018 beads showed no case of surface cracking. Substructure characteristics will be discussed later.

Air Welded Specimens. For comparison with the underwater welded specimens, identical shear fillet weld specimens were air welded both by the author and by a qualified HY-80 welder. The plates were prepared, and assembled in the same way as the underwater welded plates, and were then welded on a standard welding workstand. One assembly was single pass welded by the author, another was single pass welded by a qualified HY-80 welder. The assemblies were not preheated* or postheated. Interpass temperatures, although not measured, were quite high, i.e. all four joints were welded consecutively without any cooling period between welds. E11018 electrodes were used with a weaving gap welding technique.

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* Minimum preheat temperature for [illegible]" HY-80 steel plate is [illegible].

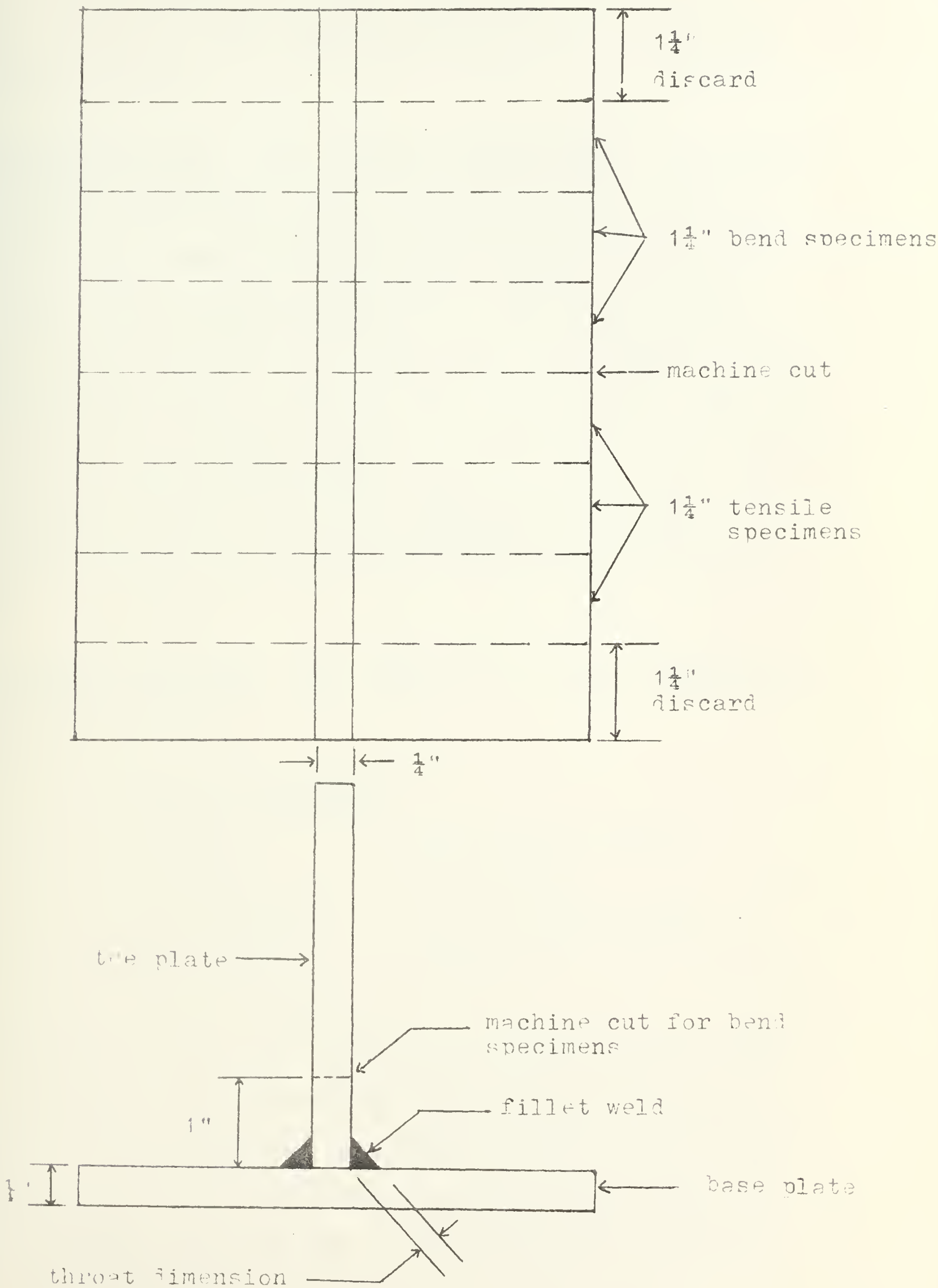
The range of electrode parameters for the air welds were as follows:

E11018 electrode	
current	120-135 Amps (DCRP)
voltage	43-48 Volts
travel speed	8.0-13.3 inches/min.
heat input	25,985-43,537 Joules/in.
ambient temp.	72.5°F

A3. Welding of ½" HY-80 Tee Joints

Tee joint specimens used for tee-bend tests and tee-tensile tests were cut from welded plates as shown in figure 5. Six specimens were cut from each plate, with three being used as tee-bend specimens and three as tee- tensile specimens. The plates were cut to size and the joint areas were pneumatically sanded and machine wire brushed to remove all primer paint and expose clean base metal. The component plates were then positioned together on a workbench and two large hand clamps were used to hold the vertical plate at 90° to the base plate. No machining of the joint was made so that the bottom edge of the vertical plate lay flush against the base plate (see figure 5). The assembly was then placed in the water tank welding tray, with the base plate positioned at a 45° angle to the horizontal welding tray to facilitate welding. The tank was filled and the joints welded with 1/8" E11018 electrodes in 8 inches of fresh water. Both single and multipass welds were made. Weldments were hand wire brushed and then machine wire

Figure 5 - Tee-bend and tee-tensile specimens.



brushed between passes, and the second pass was made in opposite sequence to the first pass as in the case of the shear fillet welds.

Surface Defects. Both single and multipass welds were made with the same power inputs as the shear lap welds but at higher travel speeds with resultant smaller bead sizes and somewhat less joint penetration. Undercut was about the same as for the shear lap specimens, but surface porosity was significantly less in size, depth and density. The weld beads were so much improved that no grinding or spot repairing were required, however weld bead appearance was still of much lower quality than the E310-16 electrode welded lap joints.

Welding Parameters. The range of electrode parameters used were as follows:

E11018 electrode	
current	180-210 Amps (DCRP)
voltage	28-36 Volts
travel speed	10.9-13.7 inches/min.
heat input	28,380-32,367 Joules/in.
ambient temp.	43.9°F

The welded plates were visually examined in the same manner described in section A2 before being cut into $1\frac{1}{4}$" specimens. In cutting the specimens for tee-tensile tests the vertical tee was left intact in order to fit into the tensile testing machine grips. On the tee-bend specimens,

the vertical tee was cut approximately 1 inch above the base plate so that the specimen would fit into the bend testing machine.

Air Welded Specimens. Single and multipass tee joints were similarily prepared and assembled, and air welded using 1/8" E11018 electrodes for comparison with the underwater welded specimens. No preheat, postheat or interpass cooling was utilized.

The range of electrode parameters used were as follows:

E11018 electrode	
current	120-135 Amps (DCRP)
voltage	43-48 Volts
travel speed	8.5-14.2 inches/min.
heat input	24,338-40,976 Joules/in.
ambient temp.	72°F

A4. Welding of 3/4" HY-80 Tee Joints

Time did not permit the welding and testing of 3/4" fillet weld shear specimens, however a series of tee-bend and tee-tensile tests were conducted on 3/4" HY-80 underwater welded tee joints. The plate dimensions were 12" x 4 3/4" with a double beveled web, as shown in figure 35, to insure adequate penetration. The plates were prepared and assembled in the same way as the ½" HY-80 tee-joints* and welded in 3 inches of fresh water with 1/8" diameter E11018 electrodes.

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*See Section A2.

Welding Sequence. Four to five passes per side were made. A full pass was made on one side of the web, then a full pass on the other side. Each pass was hand wire brushed immediately after welding, with the entire assembly being removed from the tank and machine wire brushed after each set of passes. The assembly was then replaced in the tank and the next set of passes made in opposite sequence to the preceeding set. Hand clamps were attached to the plates throughout the entire welding operation. After the second and fourth set of passes both sides of the web were ground down with a hand held pneumatic grinder. The fillet weld reinforcement was ground to a 45° angle, removing most of the surface cavities in the process. After grinding down the fourth set of passes, isolated repair welds were made to remove the deepest pits which remained.

Weaving Drag Welding Technique. As mentioned in Section A2, an electrode weaving technique was used to good advantage in the air welding of ½" HY-80 tee joints. On the final pass of the 3/4" HY-80 underwater tee joint fabrication a weaving motion was employed with the electrode drag method to determine if a weaving technique could be as advantageous in the underwater welding of relatively thick plate as it proved to be in air welding. Of course in welding any beveled joint, the electrode is physically restrained from weaving during the first few passes where the machined groove is quite narrow. However on the outer portion of the beveled joint the groove becomes wide enough so that the electrode

can be manually maneuvered. During air welding, the molten weld remains fluid long enough to fill in all the gaps caused by a weaving electrode motion. In underwater welding the molten weld metal is quenched so fast that the weld bead cannot flow and fill in all the gaps. The result is a weld bead ribbon that weaves back and forth accross the joint like a sine wave, so that another weld bead ribbon must be laid "180° out" from the first in order to completely fill in the first set of gaps. This premature solidification of the underwater weld bead nullifies the advantage of electrode weaving, that is, it still takes two or more passes to satisfactorily weld the same joint volume that can be welded in air using a weaving technique.

Welding Parameters. The range of electrode parameters were as follows:

E11018 electrode	
current	230-260 Amps (DCRP)
voltage	21-26 Volts
travel speed	6.6-8.3 inches/min.
heat input	38,591-54,363 Joules/in.
ambient temp.	42.4°F

Interpass temperature was equal to ambient water temperature.

No air weld tee joints were made.

Section B - Experimental Results

B1. Results of $\frac{1}{2}$" HY-80 Fillet-weld Shear Tests

Specimen Preparation. Fillet weld shear tests were conducted in accordance with the procedures and specifications of MIL-STD 00418B. Specimens were cut to $1\frac{1}{2}$" width and the average fillet throat dimensions measured. All four weld beads were then ground down to approximately a 45° fillet, except on the single pass underwater welded specimens. The grinding process removed almost all surface porosity, but special care was taken not to eliminate undercut. The single pass underwater welded specimens were not ground down because the weld beads were so small that hand grinding would have effected weld undercut which, as mentioned previously, has a greater effect on weld degradation than surface porosity.

Testing Procedure. All specimens were sheared under tension at room temperature on a Baldwin hydraulic testing machine and the maximum load in pounds recorded. Shear strength/linear inch and shear strength were then calculated as shown in Appendix A, and tabulated in table 3. Also included are percentages of average underwater weld shear strength vs. average air weld shear strength for various specimen series. The significance of these results will be discussed in detail in the next section.

TABLE 3A - Results of Fillet Weld Shear Tests

Specimen	Max. load to failure (lbs)	Shear strength / linear inch (lbs/in.)	Ave throat dimension (in)	Shear Strength (psi)
5A	17,500	7,000	0.1435	48,800
5B	11,800	4,720	0.1172	40,280
5C	20,300	8,120	0.1570	51,720
Average Series 5	1[illegible],5[illegible]	6,613	0.1392	46,932
6A	33,600	13,440	0.1758	76,472
6B	36,100	14,444	0.2120	68,132
6C	25,175	10,069	0.1609	62,562
Average Series 6	31,623	12,657	0.1829	69,056
7A	32,100	12,840	0.1461	87,916
7B	31,600	12,640	0.1589	79.522
7C	37,945	15,179	0.1642	92,470
Average Series 7	33,[illegible]	13,553	0.1564	[illegible],632
8A	41,460	16,584	0.1561	106,204
8B	39,280	15,713	0.1523	103,156
8C	38,770	15,508	0.1484	104,484
Average Series 8	39,837	15,935	0.1523	104,614
9A	22,565	9,026	0.1856	48,644
9B	26,842	10,736	0.1894	56,674
Average Series 9	24,7[illegible]	9,881	0.1875	52,660

Series 5 - Single pass underwater welds by author using E11018 electrodes.

Series 6 - Multipass underwater welds by author using E11018 electrodes.

Series 7 - Single pass air welds by author using E11018 electrodes.

Series 8 - Single pass air welds by qualified HY-80 welder using E11018 electrodes.

Series 9 - Multipass underwater welds by author using E310-16 electrodes.

TABLE 3E - Shear Strength Ratios

$$\frac{\text{Ave. Series [illegible]}}{\text{Ave. Series 7}} = \frac{46{,}932 \text{ psi}}{86{,}632 \text{ psi}} \times 100 = 54.2\%$$

$$\frac{\text{Ave. Series 6}}{\text{Ave. Series 7}} = \frac{69{,}056 \text{ psi}}{86{,}632 \text{ psi}} \times 100 = 79.7\%$$

$$\frac{\text{Ave. Series [illegible]}}{\text{Ave. Series 7}} = \frac{52{,}660 \text{ psi}}{86{,}632 \text{ psi}} \times 100 = 60.8\%$$

$$\frac{\text{Ave. Series 7}}{\text{Ave. Series 3}} = \frac{86{,}632 \text{ psi}}{104{,}614 \text{ psi}} \times 100 = 82.8\%$$

B2. Results of $\frac{1}{4}$" HY-80 Tee-Bend Tests

Testing Procedure. Tee bend specimens were cut from welded plates as shown in figure 5. No weld bead grinding was performed. Tee bend tests were conducted on a Blackhawk Porto-Power P182 hydraulic bend test machine. MIL-STD-00418B specifies a tee-bend test jig as shown in figure 6, for conducting these tests, however none was available either at Boston Naval Shipyard or at M.I.T. A guided bend test jig, shown in figure 7, was available and used as a substitute. The guided bend test jig is designed for bend testing flat plate butt joints, and therefore has no tee slot to prevent veering of the tee plate to one side or the other during testing. However as shown in figure 5, the narrow edge of the ungrooved tee plate lay perpendicular to the base plate and was tightly clamped in place, so that no angular distortion occurred during welding. Also during testing, the jig plunger was carefully placed at the midpoint of the tee. The result of these two procedures was a very small amount of tee plate veering during bend testing, which for the purposes of comparative analysis between underwater welded specimens and air welded specimens was insignificant. Figure 13 shows a typical angular deviation of approximately 3° from the vertical.

Results of tee-bend tests are shown in table 4. Also included are percentages of average underwater weld bend strength to average air weld bend strength for various

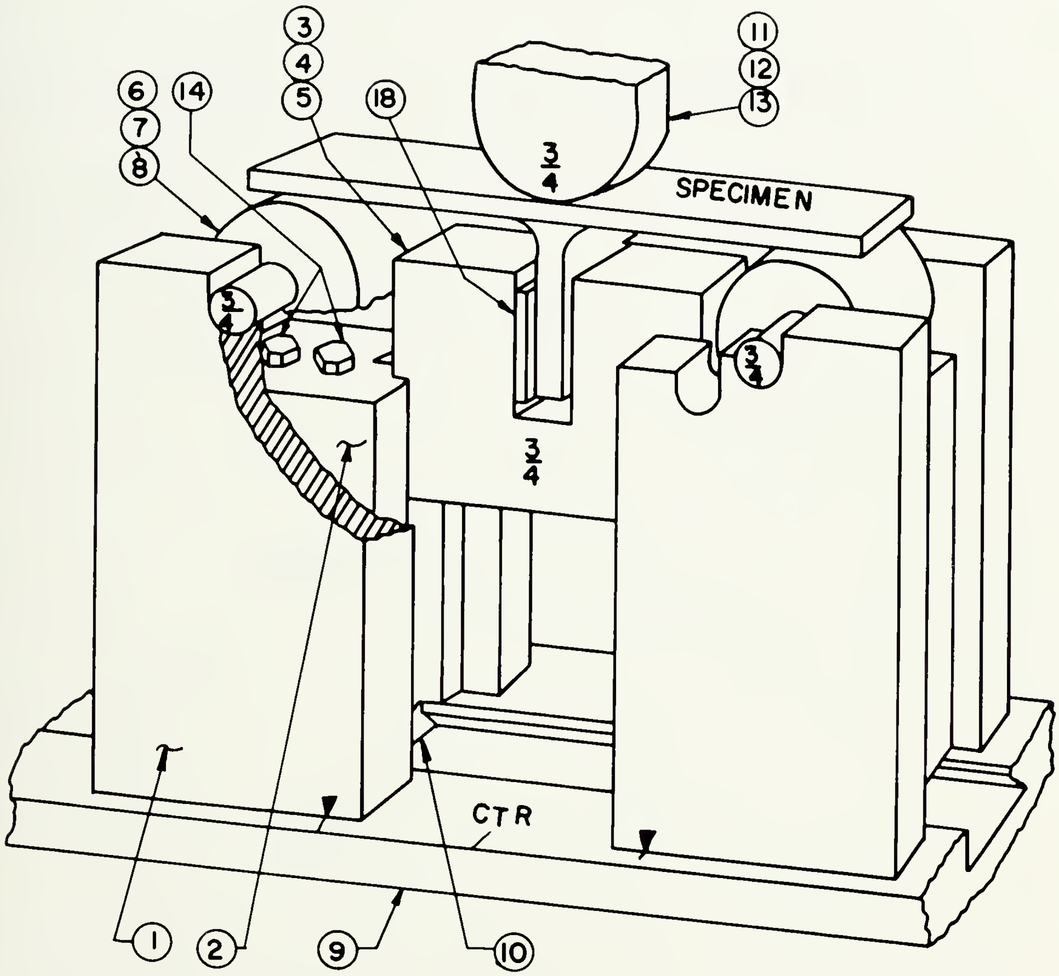


Figure 6 - Tee bend test jig.

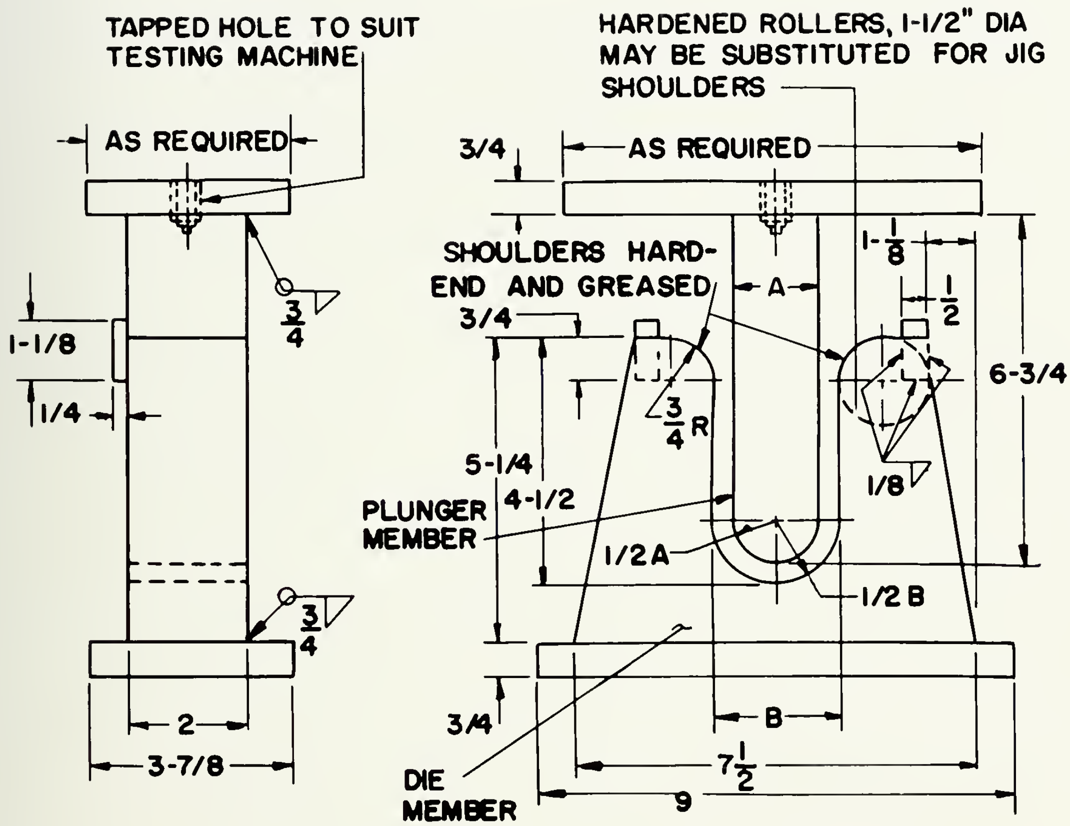


Figure 7 - Guided bend test jig.

Table 4A - Results of Tee-Bend Tests

Specimen	Fracture load (lbs)	Total bend angle at failure	Type Fracture
10A	9,894	43°	2
10B	8,590	29.5°	2
10C	8,934	32°	2
10D	8,514	30°	2
Average Series 10	8,983	33.6°	---
11A	9,254	31°	2
11B	9,365	33°	2
11C	9,548	33.5°	2
11D	10,341	46°	2
Average Series 11	9,627	35.8°	---
[illegible]	13,418	71.5°	2
[illegible]	12,897	69°	2
[illegible]	13,376	72°	2
[illegible] Series 12	13,[illegible]	70.8°	---
[illegible]	13,952	76.5°	2
[illegible]	13,362	72°	2
[illegible]	13,957	81°	2
[illegible]	13,662	71°	2
AVERAGE SERIES 13	[illegible],733	75°	---
B. P. A	14,170	180°	No Fracture
B. P. B	[illegible],978	180°	No Fracture
AVE SERIES B. P.	[illegible]	180°	---

Series 10 = Single pass underwater weld by author using E11018 electrodes.

Series 11 = Multipass underwater weld by author using E11018 electrodes.

Series 12 = Single pass air weld by author using E11018 electrodes.

Series 13 = Multipass air weld by author using E11018 electrodes.

[illegible] . . . = [illegible]-30 base plate (unwelded).

Table 4[illegible] - Tee-Bend Strength Ratios

$$\frac{\text{Ave. Series 10}}{\text{Ave. Series 1[illegible]}} = \frac{\text{[illegible],93[illegible] lb}}{\text{13,733 lb}} \times 100 = \text{[illegible]7.[illegible]}$$

$$\frac{\text{Ave. Series 11}}{\text{Ave. Series 1[illegible]}} = \frac{\text{[illegible],627 lb}}{\text{13,733 lb}} \times 100 = \text{70.1[illegible]}$$

$$\frac{\text{Ave. Series 10}}{\text{Ave. Series 11}} = \frac{\text{[illegible] lb}}{\text{9,627 lb}} \times 100 = \text{93.[illegible]}$$

$$\frac{\text{Ave. Series 1[illegible]}}{\text{Ave. Series 1[illegible]}} = \frac{\text{13,230 lb}}{\text{13,733 lb}} \times 100 = \text{96.3\%}$$

$$\frac{\text{Ave. Series 12}}{\text{Ave. B.P.}} = \frac{\text{13,733 lb}}{\text{14,074 lb}} \times 100 = \text{97.5\%} = \text{Maximum joint efficiency}$$

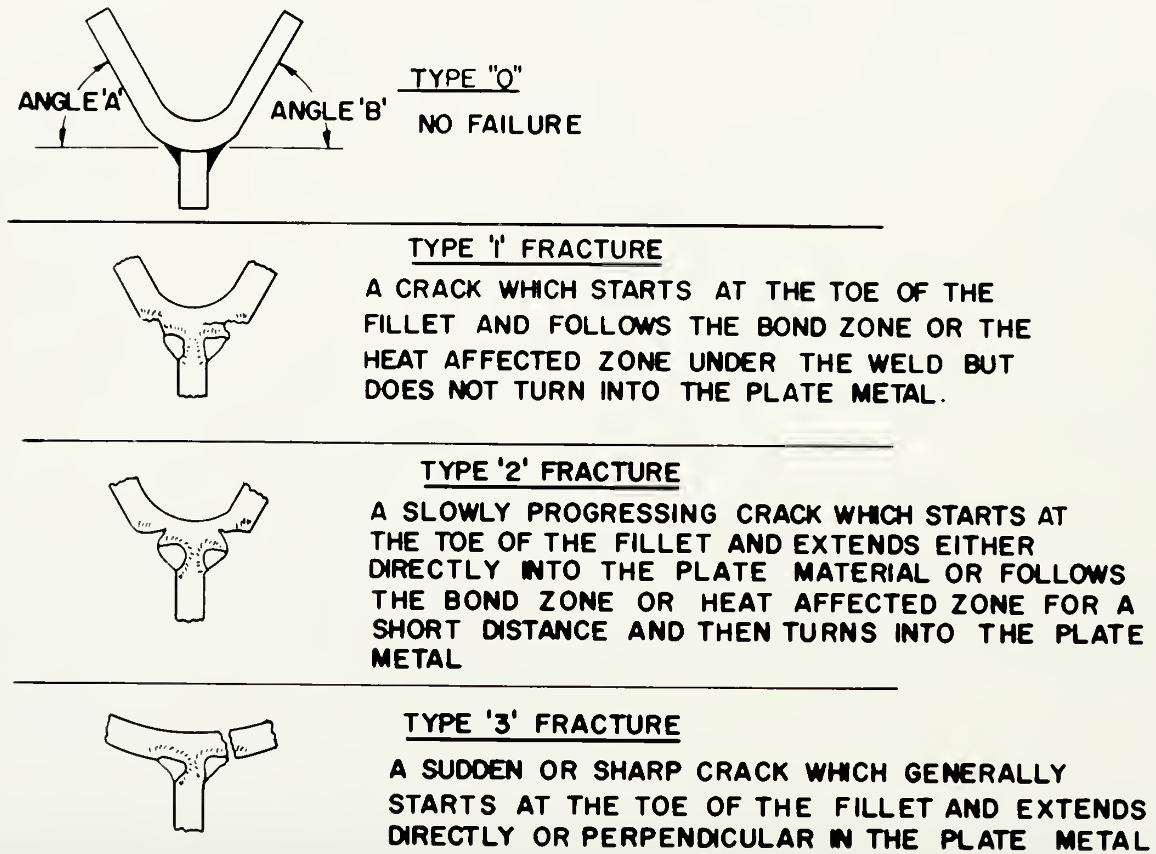


Figure 8- Types of fracture in tee-bend specimens.

specimen series. All specimens failed by Type '2' fracture as described in figure 8.

B3. Results of $\frac{1}{4}$" HY-80 Tee-Tensile Tests

Testing Procedure. MIL-STD-00418B lists no standard tee-tensile test, however for completeness of this study it was desired to conduct some form of tee tensile test to roughly assimilate the behavior of a load bearing padeye which is commonly welded to sunken hulls during salvage operations.

Since bend strength had already been tested, the goal of this test was to pull the tee joints in axial tension without any bending stresses. Unfortunately since this test is not a standard Navy test, there was no suitable grip assembly available for conducting this test at the Boston Naval Shipyard Materials Testing Lab. However lab technicians did improvise an assembly to hold the horizontal base plate, while the vertical tee plate was placed in a standard tensile grip. With this method two holes had to be drilled into the base plate, one on either side of the tee plate away from the weld zone, in order to secure a 'V' bolt to the specimen. The two holes reduced base plate crossectional area to such an extent that when loaded in tension the base plates of the first three specimens tested underwent moderate to severe bending.

Specimens 15A, 15B, 15C failed by bending at fairly low loads. During testing of specimen 15B, which was the last

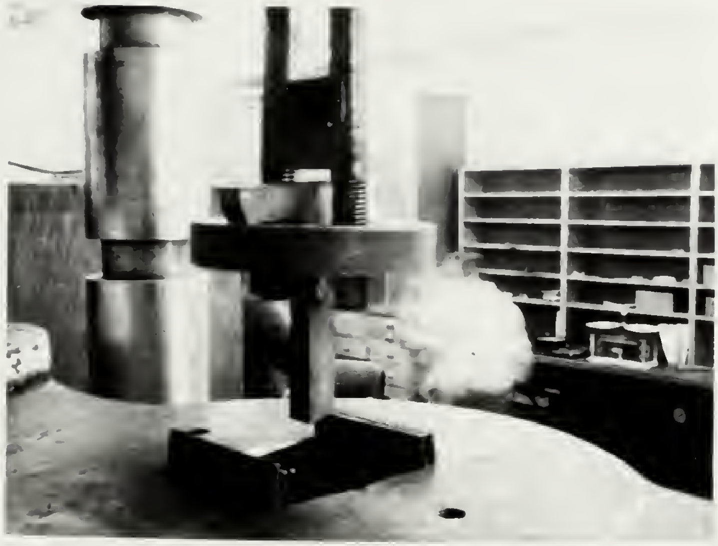


Figure 9 - Close up of improved tee-tensile testing assembly showing holding disc. 3/4" HY-80 tee joint is shown ready for testing.

Figure 10 - Entire tee tensile testing assembly with 3/4" HY-80 tee joint shown ready for testing.

specimen tested, the Vee bolt also fractured. Since base plate bending of all three specimens was asymmetric and bend angle at fracture was not measured, but merely total bend angle after removal from the testing machine, no real conclusions can be drawn from this data, except for the fact that bending greatly effects joint strength as previously determined.

After failure of the first assembly, a more substantial assembly was developed in which the base plate was completely restrained from bending. The improved assembly is shown in figures 9 & 10. The vertical tee plate is placed through a slot in the holding disc. The slot is wide enough so that it doesn't rest on the weld, and yet small enough so that specimen bending is effectively prevented, **thereby** forcing the joint to fail in shear only.

Tee tensile specimens were cut from welded plates as shown in figure 5, and tested on a SATEC SYSTEM INC, Model 60BTE hydraulic tensile testing machine. Results of tee-tensile test are shown in Table 5, with percentages of average underwater weld joint strength verses average air weld joint strength for various specimen series included.

B4. Metallography of ¼" HY-80 Air and Underwater Welded Joints

Figures 11 through 32 are macro and micro- specimens of randomly selected ¼" tee and lap joints welded with [illegible] electrodes. Figures 11 through 13 show the weld zone, joint penetration, undercut, porosity and other characteristics

TABLE 5A - Results of Tee-Tensile Tests

pecimen	Max. load to failure(lbs)	Shear strength (lbs/in.) linear inch	Ave. throat dimension(in.)	Shear Strength(psi)
14A*	15,520	6,207	0.1579	39,300
14B**	12,542	5,017	0.1356	36,996
14C***	16,500	6,600	0.1445	45,658
verage eries 14	14,854	5,941	0.1461	40,650
15A	25,520	10,208	0.1563	65,310
15B	27,356	10,942	0.1602	68,326
15C	27,060	10,823	0.1594	67,920
verage eries 15	26,645	10,657	0.1586	67,185
16A	24,620	9,848	0.1269	77,604
16B	23,925	9,570	0.1285	74,474
16C	21,775	8,711	0.1241	70,193
erage ries 16	23,440	9,376	0.1265	74,102
17A	30,670	12,266	0.1567	78,276
17B	28,200	11,280	0.1523	74,064
17C	29,120	11,774	0.1556	75,668
erage ries 17	29,330	11,771	0.1547	76,089

*3.5° Total Bend

**28° Total Bend

***9° Total Bend

ries 14 & Series 15 - Multipass underwater welds by author using E11018 electrodes.

ries 16 - Single pass air welds by qualified HY-80 welder using E11018 electrodes.

ries 17 - Multipass air welds by qualified HY-80 welder using E11018 electrodes.

Table 5B - Tee Tensile Strength Ratios

$$\frac{\text{Ave Series 15}}{\text{Ave Series 17}} = \frac{67{,}185 \text{ psi}}{76{,}089 \text{ psi}} \times 100 = 88.3\%$$

$$\frac{\text{Ave Series 16}}{\text{Ave Series 17}} = \frac{74{,}102 \text{ psi}}{76{,}089 \text{ psi}} \times 100 = 97.4\%$$

of typical air and underwater welded joints. Figures 14 through 32 show grain structures of various regions of the welds in order to compare the metallurgical characteristics of these joints. Unfortunately time did not permit the preparation of sufficient specimens so that one specimen could be etched for each particular weld region. Therefore a small number of specimens were prepared and etched to a degree that showed the grain structure of all the different weld regions. As a result one region might be slightly overetched in order to show up a more slowly etching adjacent region. Thus the quality of etch will vary from zone to zone, however the general trends of each region are apparent.

Figures 33 and 34 show Vickers hardness through various specimen weld zones in order to correlate grain structure to hardness for air and underwater welds.

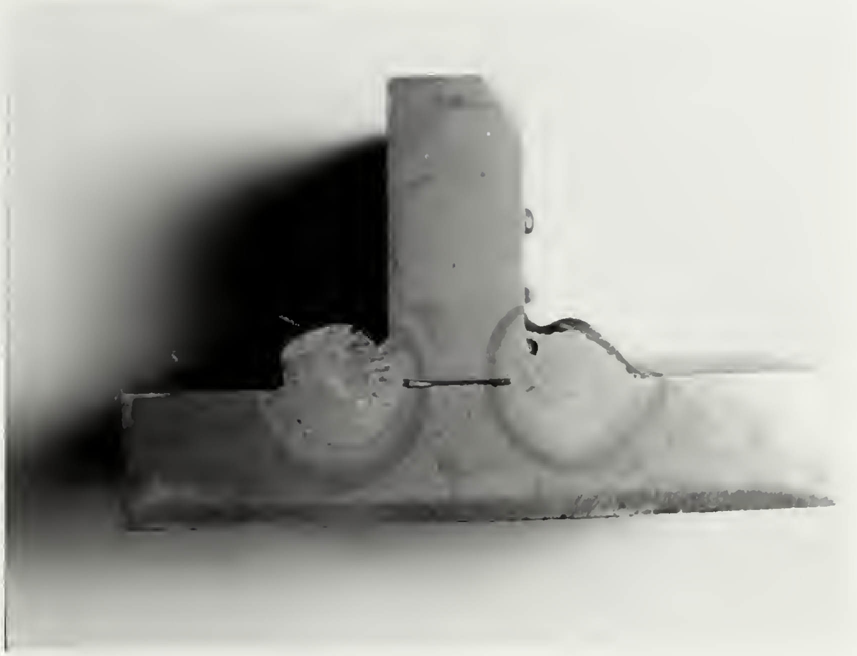


Figure 11 - Single pass underwater welded tee joint using E11018 electrode. (3x, 3% Nital etch)

Figure 12 - Single pass underwater welded tee joint using E11018 electrode. (3x, 10% HCL etch)

Figure 13 - Single pass air welded tee joint using E11018 electrode. (3x, 3% Nital etch)

Figure 14 - HY-80 base metal. (200x, 1% Nital etch)

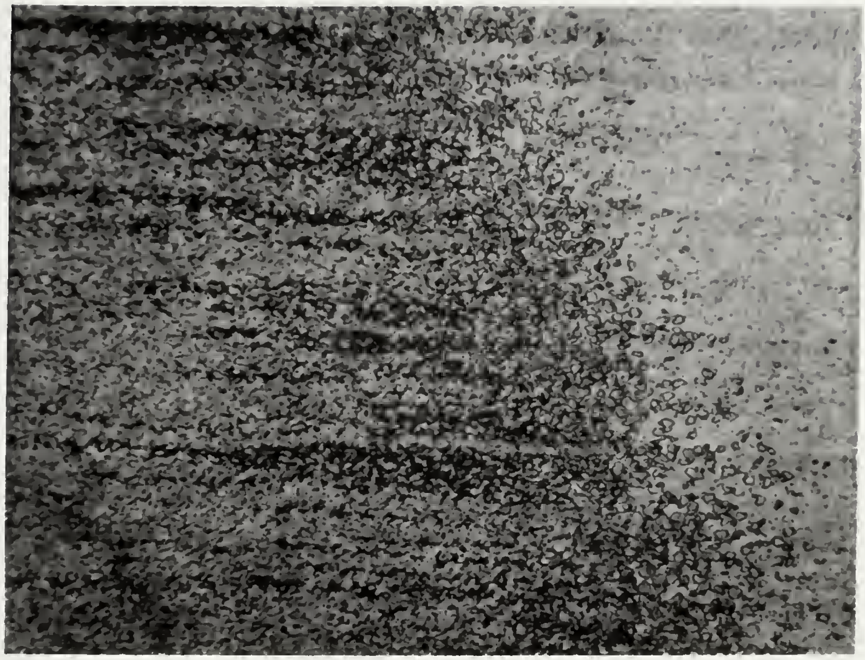


Figure 15 - Single pass underwater weld heat affected zone (left) - base metal interface. (200x, 1% Nital etch)

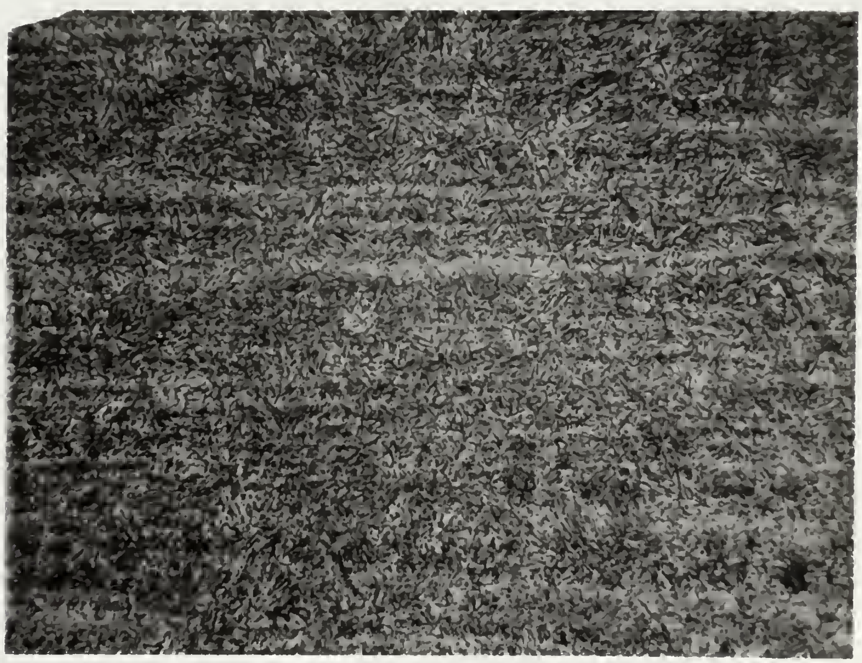


Figure 16 - Single pass underwater weld heat affected zone. (200x, 1% Nital etch)

Figure 17 - Single pass underwater weld heat affected zone (top-left) - weld metal interface. Note heavy grain boundaries in HAZ. (200x, 1% Nital etch)

Figure 18 - Single pass underwater weld metal. (200x, 1% Nital etch)

Figure 19 - Single pass underwater weld metal showing porosity (lower right) and dendritic grain growth. (50x, 1% Nital etch)

Figure 20 - Single pass underwater weld metal showing a region of dense porosity. (50x, 1% Nital)

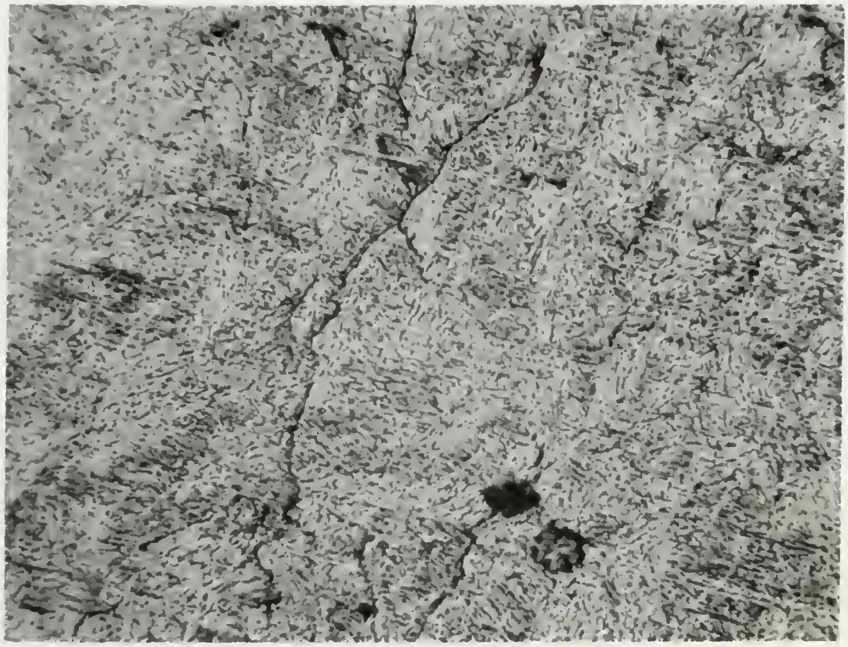


Figure 21 - Single pass underwater weld metal showing intergranular microcracking - porosity at lower right initiated microcracks. (200x, 1% Nital etch)

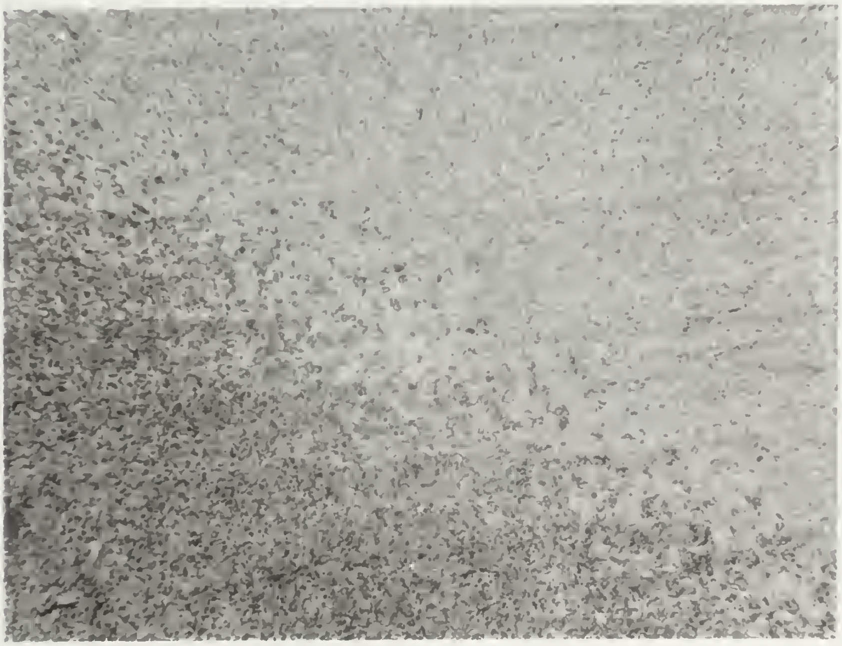


Figure 22 - Single pass air weld heat affected zone (left)-base metal interface. (200x, 1% Nital etch)

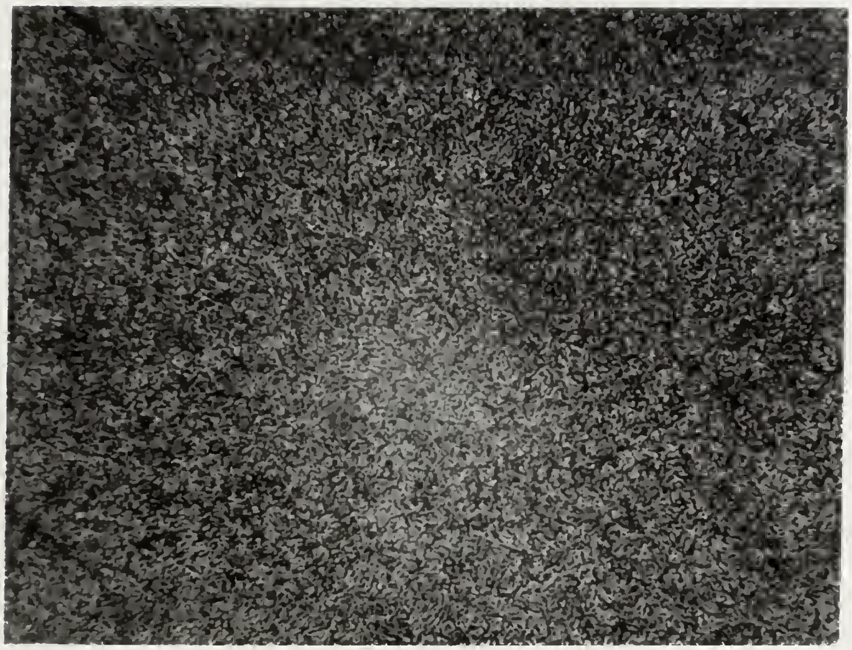


Figure 23 - Small grained region of heat affected zone in a single pass air weld. (200x, 1% Nital etch)

Figure 24 - Intersection of small grained-large grained regions of heat affected zone in a single pass air weld. (200x, 1% Nital etch)

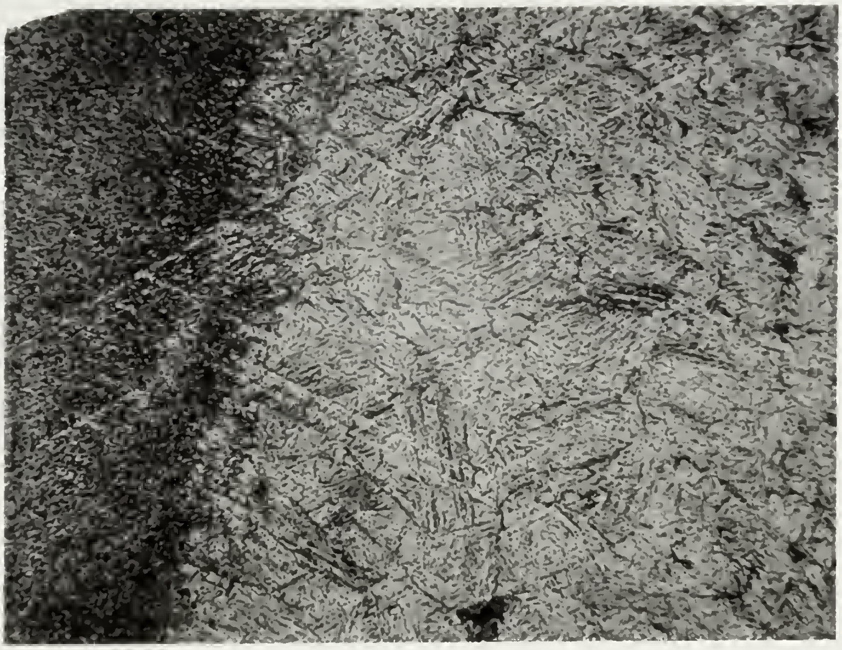


Figure 25 - Single pass air weld heat affected zone (right)-weld metal interface. (200x, 1% Nital etch)

Figure 26 - Single pass air weld large grained region of heat affected zone showing a region of dense porosity but no microcracking. (200x, 1% Nital etch)

Figure 27 - Multipass underwater double fillet lap joint using E11018 electrodes. (2.75x, 3% Nital etch)

Figure 28 - Multipass underwater weld base metal (top) - first pass HAZ interface. (200x, 1% Nital etch)

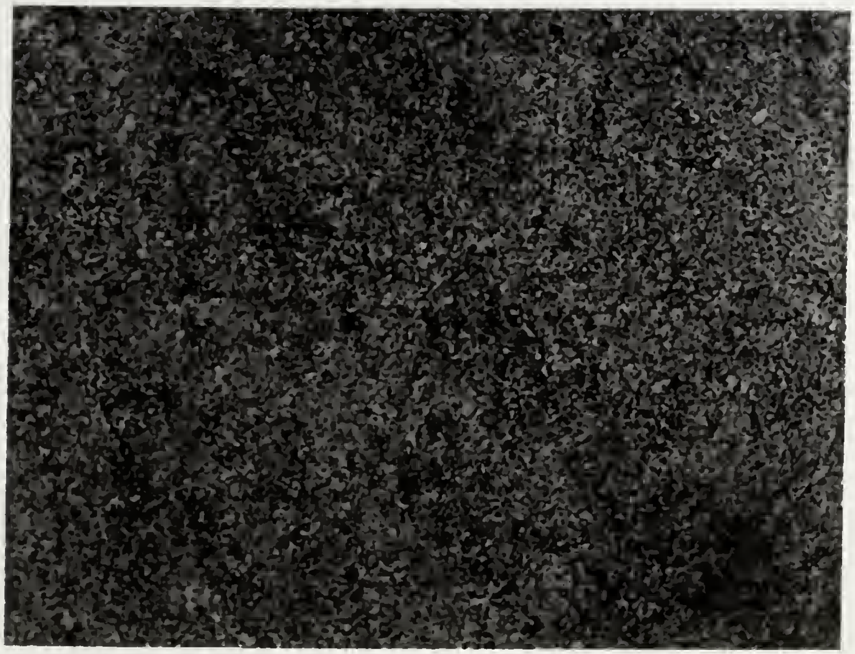


Figure 29 - Multipass underwater weld first pass heat affected zone. (200x, 1% Nital etch)

Figure 30 - Multipass underwater weld showing first occurrence of second pass HAZ grains over first pass weld metal. (200x, 1% Nital etch)

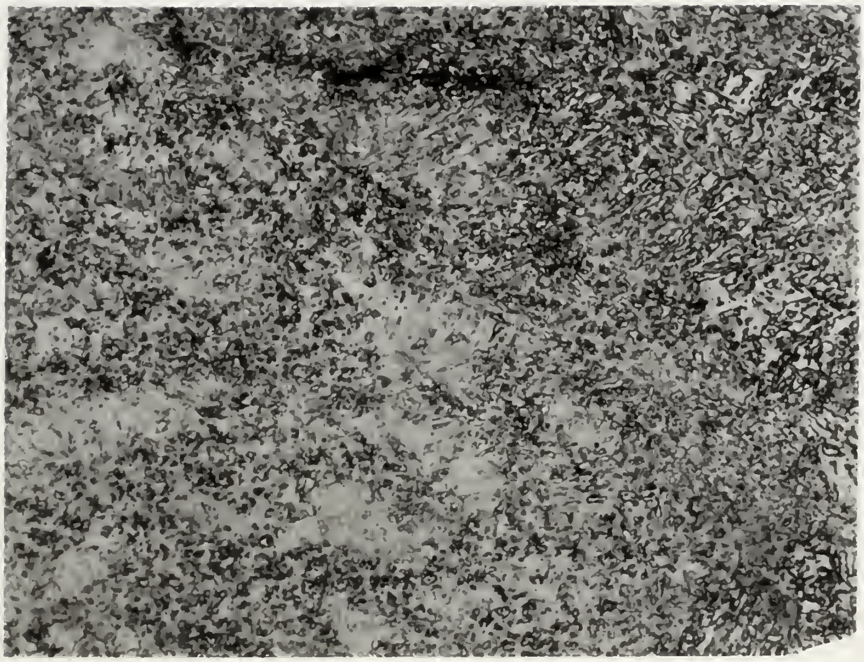


Figure 31 - Multipass underwater weld showing center of second pass HAZ-first pass weld metal overlap region. (200x, 1% Nital etch)

Figure 32 - Multipass underwater weld showing dendritic grain growth in second pass weld metal. (Black dots are polishing powder particles, not porosity) (100x, 1% Nital etch)

FIGURE 33 - WELD ZONE HARDNESS FOR SINGLE PASS WELDS

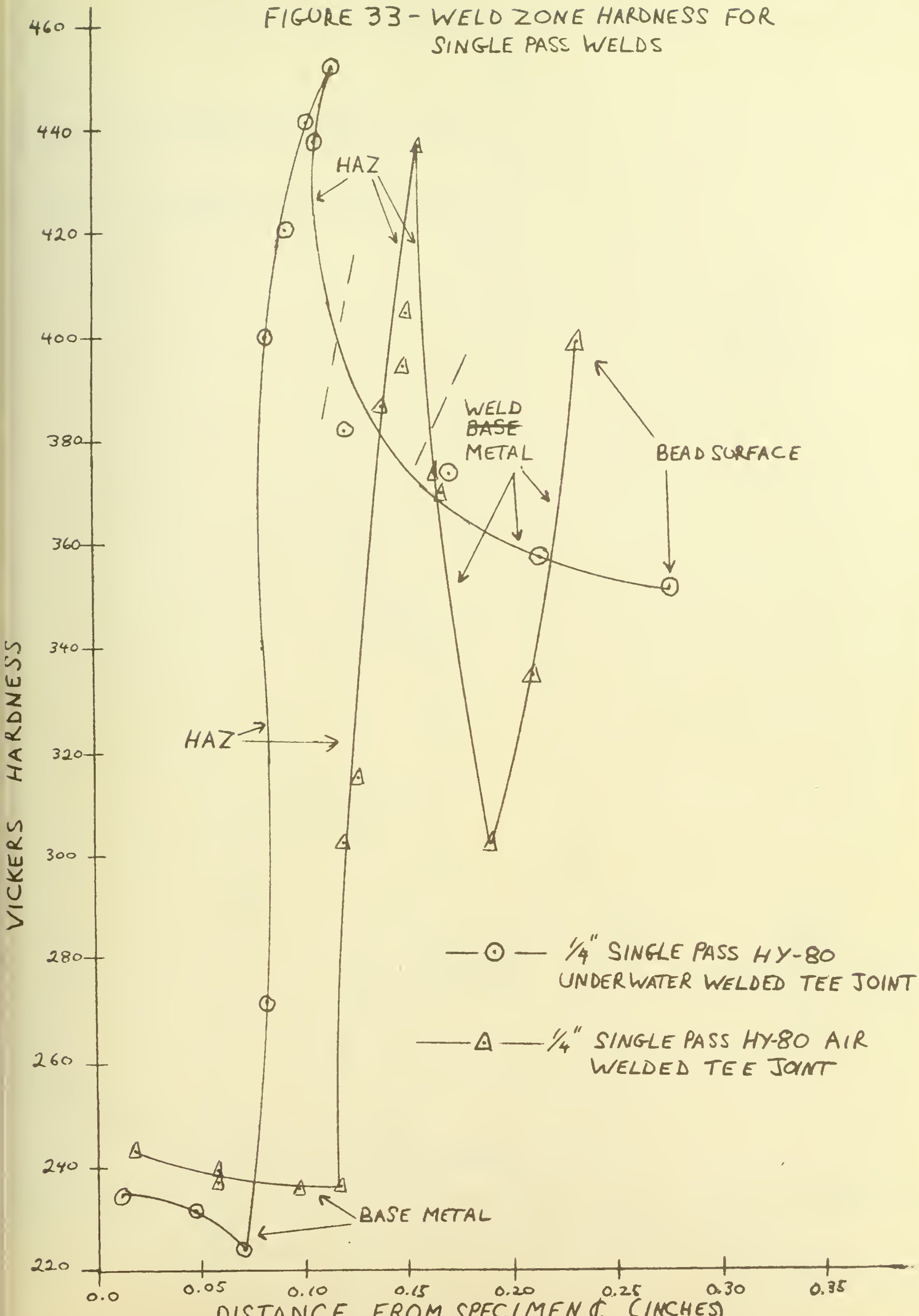
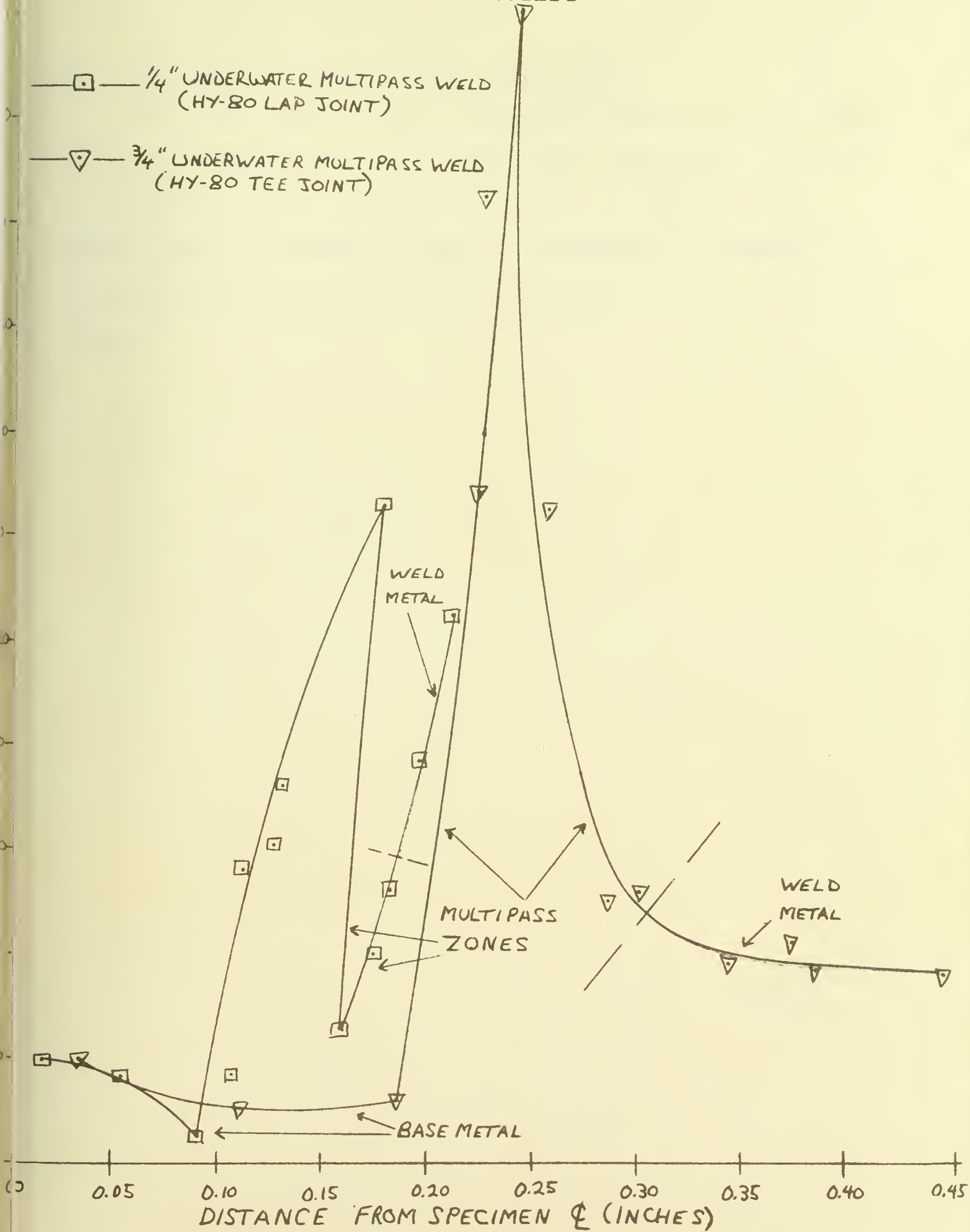


FIGURE 34 - WELD ZONE HARDNESS FOR MULTIPASS WELDS



B5. Results of 3/4" HY-80 Tee Joint Tests

3/4" HY-80 tee-bend and tee-tensile test were conducted in the same manner as the ½" HY-80 test specimens. Results of tee-bend test are shown in Table 6. Results of tee-tensile test are shown in Table 7. Figures 35 through 38 are macro and micro-specimens of randomly selected 3/4" tee joints.

Table 6 - Results of Tee-Bend Tests

Specimen	Fracture load (lbs)	Total Bend angle at failure	Type fracture
18A	37,858	9°	3
18B	38,550	9.5°	3
18C	36,519	8°	3
Average Series 18	37,642	8.8°	---
B.P. A	64,275*	42°	No Fracture
B.P. B	64,275*	39°	No Fracture
Average Base plate	64,275*	40.5°	---

*Rated capacity of bend testing machine

Series 18 = Multipass underwater weld by author using E11018 electrodes.

Series B.P. = 3/4" HY-80 base plate (unwelded)

Table 7 - Results of Tee-Tensile Tests

ecimen	Max. load to failure(lbs)	Shear Strength linear inch $(\frac{lbs}{in.})$	Ave. throat dimension(in)	Shear Strength(psi)
9A	28,730	11,493	0.5078	22,632
9B	21,910	8,762	0.4296	20,395
9C	18,915	7,566	0.3711	20,388
erage ries 19	23,185	9,273	0.4361	21,138

eries 19 = Multipass underwater weld by author using E11018 electrodes.

Figure 35 - Multipass underwater welded 3/4" tee-joint using E11018 electrode. (2x, 3% Nital etch)

Figure 36 - Region of porosity, slag inclusions, and poor fusion in 3/4" multipass underwater welded tee joint. (200x, 1% Nital etch)

Figure 37 - Region of dense porosity and slag inclusions in 3/4" multipass underwater welded tee joint. (200x, 1% Nital etch)

Figure 38 - Lines of continuous slag inclusions along base plate-weld metal interface which prevented proper weld fusion of 3/4" underwater welded tee joint. (200x, 1% Nital etch)

Section C - Discussion of Test Results

C1. $\frac{1}{4}$" HY-80 Fillet Weld Shear Tests

Single Pass Underwater Welds. It is first apparent that the single pass underwater fillet weld had extremely poor shear strength. There were a number of reasons for this including inadequate penetration, off-center weld bead positioning, and excessive undercut. The first two problems can be greatly reduced by welding technique and welder experience, as is demonstrated by the improved performance of single pass tee-bend and tee-tensile specimens which were welded after the shear specimens.

Multipass Underwater Welds. More encouraging was the performance of the multipass shear specimens in which penetration was adequate, the wider bead positioned correctly, and the effects of undercut lessened. The average shear strength of these specimens was 79.7% of comparable single pass air-weld specimens also welded by the author. The Navy Underwater Cutting and Welding Manual (NAVSHIPS 0929-000-8010) accepts an underwater welded mild steel joint with 80% the strength of a similar air-welded joint. The initial value of 79.7% for the HY-80 shear specimens correlates well with the minimum value of 80% set for mild steel joints. Also of note is the fact that all series except series 12 were welded by the author. Series 12 was welded by a Navy qualified HY-80 welder. A difference in shear strength of 18% was

found between the air welds made by the author to those made by the qualified welder. It is reasonable to assume that an approximate gain of 18% in the shear strength of underwater fillet welds could be achieved by a professional underwater welder, qualified to weld HY-80 steel.

Air and Underwater Welding Techniques. The reason multipass underwater welds are compared to single pass air welds in this case is that with the air welded specimens an adequate and acceptable joint was made with a single pass. An acceptable single pass underwater weld would have been preferred but was unattainable. It was found that use of the drag technique, which is required in low visibility underwater welding, inhibits the welder from weaving the electrode along an ungrooved joint fit-up, as is frequently done in air welding. This electrode weaving technique can be effectively used to produce a large fillet bead relative to electrode diameter as shown in column 4 of Table 3A. The advantage of the weaving technique is to increase welding heat input without causing burnthrough of relatively thin steel plate. The weaving technique was used in the multipass underwater welding of 3/4" HY-80 grooved tee joints, but success was limited.*

*See Section A4.

Effects of Weld Undercut. Although higher current settings and lower travel speeds would increase weld penetration and produce a larger fillet, it would not reduce, and in extreme cases, even increase weld undercut. All underwater welds in both mild steel and HY-80 had excessive undercut, which appears to be an unavoidable problem even under optiminzed welding conditions. The single pass underwater welds produced small fillet beads which resulted in undercut close to the joint, as shown in figure 39. When tensile stress is applied to the shear specimens the undercut grooves act as continuous notches paralleling both sides of the weld bead. The notch roots cause local stress intensities which greatly reduce joint fracture toughness, resulting in premature shear fracture. By using multipass welds, undercut can be "pushed away" from the joint area and cut into the base plate material (see figure 40). Thus the effects of undercut on the joint are lessened, while the tougher base plate material can better withstand the local notch effect.

Effects of Reduced Visibility. The underwater welding of thin plate lap joints is made extremely difficult by reduced visibility. A few seconds after arc initiation the entire weld line becomes shrouded by a dense cloud of suspended flux particles which forces the welder to weld by "feel". Silva[8] notes that the flux particle is so small that

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[8]Silva, op. cit., pp 68.

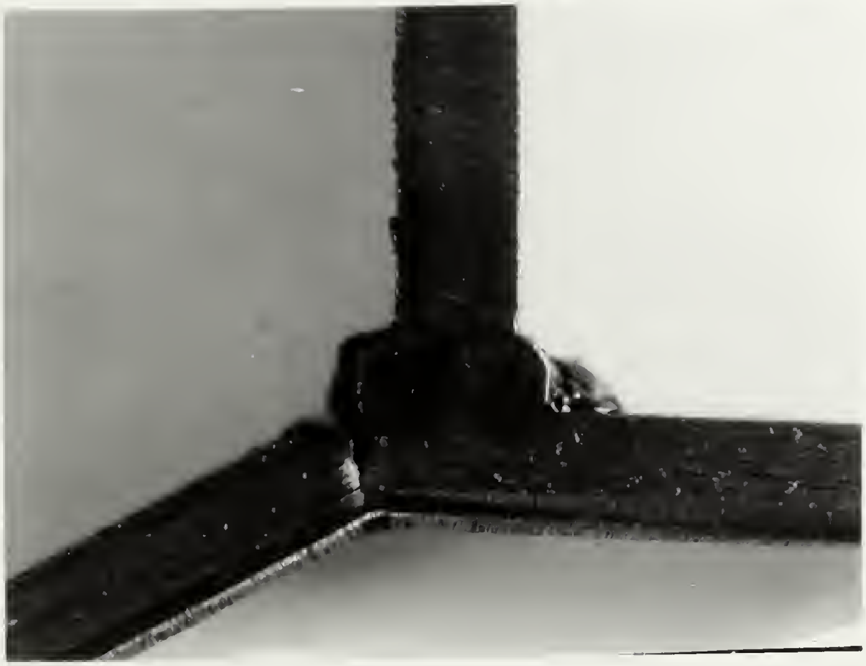

Figure 39 - Single pass underwater weld showing excessive undercut close to plate intersection. Bead profiles for fillet weld lap joints are similar to those for fillet weld tee-joints.

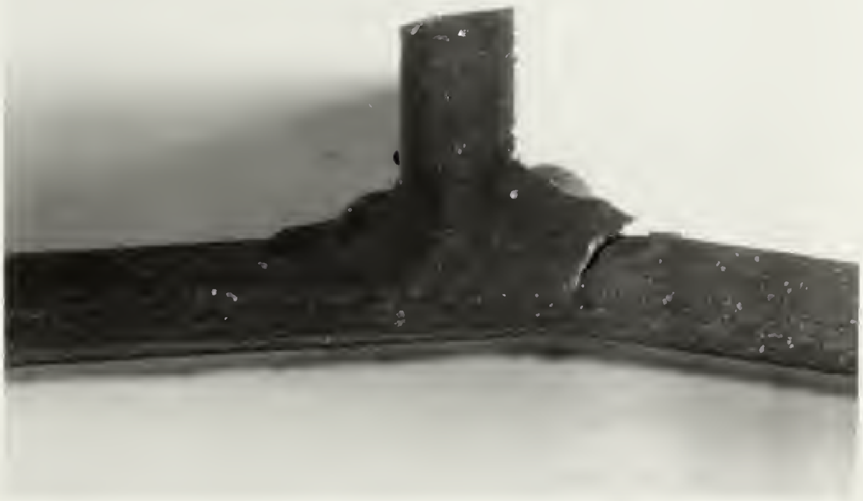

Figure 40 - Multipass underwater weld showing small degree of undercut further away from plate intersection.

it cannot be filtered from the water by conventional mechanical means. In the case of tee joints the top of the tee will usually remain above the flux cloud, even in a small test tank, and the welder can judge the position of the joint by mentally extending the exposed tee section on a straight line to the base plate. Thus the welder has a visual point of reference with which to combine with the "feel" of the dragging electrode. This greatly facilitates the problem of accurately placing the weld bead in the case of tee joints. However with lap welds the entire joint and surrounding plates are completely enshrouded and even with the use of an electrode guide it is difficult to stay on the weld line. Within a few seconds of arc initiation there is no longer any point of reference and with two degrees of motion for the welder to control (i.e. electrode travel and electrode melt down) the usual result is a wavering weld bead which regularly wanders away from the desired weld line and causes gaps in the weld. In multipass welding these gaps are closed by subsequent passes and a more even and uniform weld is achieved.

<u>Single Pass vs. Multipass Underwater Welding</u>. Thus the beneficial effects of multipass welding are threefold, while the main adverse effect is increased porosity in the weld zone, particularly the weld metal. While it is not impossible to make an acceptable single pass lap weld using a larger electrode size and higher heat input, even a qualified

welder under good operational conditions would have to limit the length of his weld beads to fairly small lengths in order to periodically realign himself. This is one reason why the Navy Underwater Cutting and Welding Manual* recommends first bolting a cover plate patch in place before fillet welding during all underwater repair operations. Also during voyage repairs or salvage operations joint fit-up may be so poor, especially when repairing shaped hull plates, that multipass welding may be mandatory. The point to be emphasized is that many things have to go right for a single pass underwater fillet weld to even be practical, much less acceptable.

Underwater Welding with Austenitic Stainless Steel Electrodes. Results of Series 10 specimens utilizing E11018 electrodes showed that the shear strength of this series was nearly equal to the ultimate tensile strength of the E310-16 austenitic stainless steel electrodes and therefore the shear strength of Series 13 specimens were expected to be unacceptably low. Test results confirmed this expectation, however if the E11018 electrodes had proven totally unacceptable for use in underwater welding of HY-80 steel, the E310-16 electrode would have proven itself capable of providing at least some degree of underwater weld shear strength.

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*See pages 6-24, Navy Underwater Cutting and Welding Manual.

C2. $\frac{1}{4}$" HY-80 Tee-Bend Tests

The significant characteristic of the tee-bend test is that it measures solely weld surface quality. The specimen is simply supported at each end and loaded at the center so as to place the entire weld surface in bend tension. The maximum load to failure, the type of fracture, and the bend angle at fracture initiation are then recorded and give a good indication of the effects of surface defects. As mentioned previously, tee joints could be much more easily underwater welded than lap joints. In addition, two underwater welding modifications were employed on the tee joints, which increased weld quality. The first was that in single pass underwater welds a slower travel speed was used with the same current input as for the lap joints. This increased joint penetration as well as weld bead size, with no notable increase in surface porosity or decrease in weld undercut. The second was the discovery that higher electrode travel speeds during multipass underwater welding greatly reduced surface porosity (but not undercut) on the second pass.

Effects of Hydrogen Entrapment on Weld Quality. Obviously less heat input causes less hydrogen disassociation in the vapor saturated welding arc, and therefore less hydrogen entrapment in the weld zone. In addition the smaller weld bead presents less of an obstacle to escaping

arc gases[9]. Apparently the diffusion rate of the hydrogen gas is sufficiently higher than the quenching rate of the weld metal, so that the percentage of entrapped hydrogen gas decreases rapidly with decreasing bead size. Rapid quenching in a water environment prevents any rise in overall plate temperature as the weld progresses. Thus there is no preheating effect ahead of the welding arc as there is in air welding. It can be then argued that for reasonable variations in underwater welding travel speed, the peak plate temperature under the arc will remain relatively constant along the entire joint and therefore the quenching rate will be essentially constant for different travel speeds and weld bead sizes. The result is that a larger weld bead will have more hydrogen gas entrapped deeper within the molten weld metal which is cooling at the same rate as a smaller weld bead. The conclusion is that from the standpoint of porosity two small weld beads, providing adequate penetration, is better than two large weld beads. Of course if post-weld surface peening or grinding can be accomplished, higher porosity could be tolerated in return for deeper penetration.

Effects of Weld Undercut on Weld Quality. The tee bend test came the closest to isolating the effect of weld undercut

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[9]Kemp, op. cit., pp 145, found that these gases are 62-82% hydrogen.

on fracture initiation and propagation in underwater welds. As shown in figures 11 through 13, air welded tee specimens had very slight undercut with no real undercut notch. The underwater welded specimen has deep undercut with sharp notch roots. The degradation of bend strength in the underwater welds verses the air welds is therefore a good indicator of the underwater welded joint notch sensitivity.

Table 4A shows that base metal bend strength is greater than that of any welded specimen. Thus in no case was 100% joint efficiency attained, and welded tee joints will degrade bend strength to a degree proportional to weld surface quality. MIL-STD-00418B does not take into account weld bead size in bend strength calculations. However it can be seen from Table 4 that weld bead size is not significant since for air welds (no undercut) single pass bend strength is 96.3% of multipass bend strength, even though the average multipass throat dimension was 21% larger than that of the single pass series. The overall loss in bend strength for single pass and multipass underwater welds was 32.1% and 29.9% respectively compared to air welds. Therefore weld degradation due to surface defects is significant, i.e. an average of 31% for single and multipass welds. For air welds the average loss in joint efficiency over HY-80 base plate is only an average of 5.2% for single and multipass welds. Table 4B shows that the multipass underwater welds had a 6.7% higher bend strength than single pass underwater welds due partly to the larger fillet size and partly to the smaller, further removed

undercut notch.

Decrease in Underwater Weld Ductility. It is interesting to note that while ratio of bend strengths was 69% between air and underwater welds, the ratio of bend angle at failure was 47.5%. Therefore loss of ductility is approximately 22% greater than loss in bend strength for underwater welds. At first glance this seems unsatisfactory, however when comparing single and multipass air welds to HY-80 base plate the ratios of bend angles is only 41%, so that the loss in ductility is approximately 44% greater than loss in bend strength compared to HY-80 base plate. Thus the best that can be hoped for in underwater welding is to achieve air weld bend strength and ductility, which has proven satisfactory in years of operational service, even though percentagewise air weld tee joint ductility appears to be seriously degraded.

C3. ¼" HY-80 Tee Tensile Tests

Tee tensile tests were conducted in order to determine relative tee joint strength in the absence of bending. In this way the effects of undercut would be minimized, if not eliminated during testing. Figure 11 shows that each weld bead has two undercut notches, one at each fillet toe. The top undercut notch root is placed in local compression when an axial load is applied and crack initiation and propagation is effectively inhibited. The bottom undercut notch root acts as a local stress intensifier, and in the case of base plate bending did indeed initiate fracture in tee-bend

specimens and in the bent tee-tensile specimens. However when bending was physically prevented by the restraining disc shown in figure 9, experimental results showed that fracture did not in fact initiate at the bottom toe notch, and therefore was not the "weak link" in the joint. The weal link in this series of tests was the vertical weld leg. In other words the weld leg sheared before the bottom notch root stress reached $\sigma_{crit.}$ This is reasonable because the notch root is oblique to the stress field, and the resultant stress acting perpendicular to the notch root is significantly less than the shear stress acting on the vertical fillet leg. Fracture surfaces of both air and underwater welded tee tensile specimens are shown in figure 41.

Underwater Weld Shear Strength vs Bend Strength. Especially noteworthy is the fact that in the absence of bending, the multipass underwater welds had a shear strength equal to 88.3% the shear strength of the multipass air welds. This is an 11.7% degradation in joint strength due to axial shear compared to a 31% degradation in joint strength due to bending. Therefore underwater weld undercut accounts for almost 75% of the total tee joint strength reduction. The need for minimizing undercut is apparent.

The most encouraging discovery of this investigation was that underwater weld undercut could be greatly reduced through improved welding techniques and optimization of welding parameters for a particular joint configuration and plate thickness. Even during the short time of this

Figure 41 - Side view of fractured air welded (top) and underwater welded (bottom) tee-tensile specimens. In both cases fracture occurred at vertical fillet legs.

investigation a noticable reduction in severity of undercut was obtained by the author just from the experience of welding in a laboratory test tank. Of course a great deal more research and training will be necessary before an actual field repair is ever attempted.

It was assumed in Section 3A that the maximum shear strength of a multipass air weld would not be significantly greater than a single pass air weld provided joint penetration was adequate. As shown in Table 5 the ratio of single pass air weld to multipass air weld was 98.4%. In the case of pure bending the ratio was 96.3%. The total difference assuming superposition of bend and axial stresses, is 5.3%. Therefore in the case of the fillet weld shear specimens a multipass air weld could be expected to have only about a 5% increase in shear strength over a single pass specimen for approximately a 50% increase in cost, since these specimens fractured through undercut root crack initiation and propagation induced by axial shear stresses.

C4. Metallographic Analysis of ½" HY-80 Welded Joints

Single Pass Air and Underwater Welds. Experimental test results show that approximately 31% of underwater weld degradation was caused by undercut and 11.7% from changes in internal weld structure and defects. Figures 11 and 12 illustrate the varying degrees of undercut, porosity, weld zone grain structure, and joint penetration resulting from single pass underwater welds made with similar heat inputs.

The left-hand bead of figure 11 shows the normal degree of undercut associated with single pass underwater welds. Note the fairly deep notches and sharp crack roots at both fillet toes. The right hand bead of figure 11 and the left hand bead of figure 12 are well shaped beads with little or no undercut and closely resemble the typical air weld bead shapes illustrated in figure 13. The right hand bead of figure 12 shows two cases of excessive undercut. The undercut on the bottom fillet toe is so severe that it extends below the weld. (Close examination of the specimen shows that the crack-like extension is in fact weld undercut, rather than a crack which propagated during solidification from the large notch immediately above it). Porosity and dendritic grain growth are present in the underwater weld metal and there is a continuous increase in grain size through the heat affected zone from the base metal interface to the weld metal interface. The latter is clearly defined by a line of large, non-dendritic grains, which appears rather porous, but in fact is not.

Each weld bead of figures 11 and 12 was welded at the same input (same welding parameter and ambient water temperature, and by the same welder) yet one bead on each specimen was relatively undercut free while the others were deeply undercut. It is therefore apparent that weld undercut can be largely eliminated by proper and consistent welding procedure. This is more easily said than done, because even under controlled laboratory conditions,and welding in just

a few inches of water, it was beyond the ability of the author to lay down a consistently good weld bead, mainly due to excessive turbidity.

The main characteristics of single pass underwater weld zones are as follows;

a. Heat affected zone grain size is considerably smaller than base metal grain size at base metal interface (See figures 14 and 15).

b. Heat affected zone grain size increases uniformly from the base metal interface to the weld metal interface. At the latter, HAZ and weld metal grain sizes are nearly equal, with the HAZ grain structure being the smaller of the two. Grain structure is highly directional through the heat affected zone (See figures 16 and 17).

c. Weld metal structure is characterized by large, dentritic grains with heavy grain boundaries, and is laced with porosity and microcracks, however no microcracks were observed extending into the heat affected zone (See figures 17 through 21).

d. Figure 17 shows a line of heavy grain boundaries in the heat affected zone side of the HAZ-weld metal interface similar to those found by Masubuchi and Martin[10] in the heat affected zone of air welded HY-80 weldments. These heavy grain

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[10]Masubuchi and Martin, op. cit. pp. 1-18

boundaries may be an initial stage of intergranular cracking, although no definite cracking was observed in this region.

e. Figure 21 shows intergranular microcracking in the weld metal. Note that porosity in the lower left hand corner has initiated microcracking. Very little porosity and no case of microcracking was observed in the heat affected zone or base metal of any underwater weld. This is in direct contrast to the findings of Masubuchi and Martin, where no case of pure weld metal cracking was found in an extensive survey of air welded HY-80 joints.

The main characteristics of single pass air weld zones are as follows;

a. Heat affected zone grain size is considerably smaller than base metal grain size at the base metal interface, resembling the underwater weld case except that grain structure is much less directional (See figure 22).

b. The heat affected zone consists of two distinct regions. The region closest to the base metal (light ring in figure 13) has a small grain size which increases uniformly toward the weld metal (See figures 22 and 23). About two-thirds of the way through the heat affected zone (dark ring in figure 13) there is a sudden change in grain

size as shown in figure 24. The change in grain size is about fivefold and the large grains continue to increase uniformly all the way to HAZ-weld metal interface. There is no directional grain structure in either region of the heat affected zone except at the above interface. There was some porosity in the large grain region, but no case of microcracking was observed. Also grain boundaries were not as heavy as those found in the underwater weld heat affected zone.

c. Weld metal grain size is small, comparable to the small grained region of HAZ. Heat affected zone grain size at the HAZ-weld metal interface is quite large, comparable to the weld metal grain size in an underwater weld. Very little porosity and no case of microcracking was observed in the weld metal. Grain structure was non-directional (See figures 25 and 26).

Multipass Underwater Welds. The main characteristics of multipass underwater weld zones are as follows;

a. There is extensive porosity throughout the weld zone, plus lack of fusion on the bottom fillet. The occurrance of microcracking in the multipass zones was less than that found in the single pass underwater weld metal (See figure 27).

b. Grain size of first pass heat affected zone is

similar to single pass HAZ, but the former has much less directional grain growth (See figures 28 and 29). The first pass HAZ grain structure appeared to be largely unaffected by subsequent welding passes. No case of microcracking was found in this region.

c. Multipass regions shown in figures 30 and 31 are composed of both large and small grained regions due to the overlapping of large grained weld metal over small grained HAZ regions and vice versa. This probably accounts for the lower peak hardness shown in figure 34. Also the occurrance of heavy grain boundaries in multipass regions was rare. The composition of the multipass regions results in less hardness and therefore less cracking during quenching than single pass welds.

d. No dendritic grain growth occurred in the multipass regions however the second pass weld metal region had extensive dendritic grain growth equal to that of single pass weld metal (See figure 32).

Air and Underwater Weld Zone Structures. The main metallurgical difference between underwater and air welds are the radically different heat affected zone grain structures, the large difference in weld metal grain size, and the highly directional and dendritic structure of the underwater weld zone. Also the underwater weld metal was

much more porous and laced with intergranular microcracks. These are the differences which account for most of the 11.7% loss in joint strength attributed to underwater weld structural changes.

Air and Underwater Weld Zone Hardness. Figures 33 and 34 show Vickers hardness for various air and underwater welds. Figure 33 shows that the maximum hardness occurs in the heat affected zone of both air and underwater welds. In the case of the underwater weld, maximum hardness occurs in the region of largest grain size, just before the HAZ-weld metal interface. For the air weld maximum hardness occurs in the center of the large grain region of the heat affected zone. A number of other interesting results are observed namely;

a. For both welds, base metal hardness decreases slightly as HAZ interface is approached.

b. Maximum underwater weld hardness was greater than maximum air weld hardness even though air weld grain size was considerably larger at the points of maximum hardness.

c. Underwater weld metal hardness decreased considerably between the HAZ interface and bead surface, while air weld metal hardness decreased to a secondary minimum at the center of the weld metal region and then quickly rose as the bead surface was approached.

d. The multipass fillet weld shear specimen showed a

significantly lower maximum hardness in the multipass zones, apparently because of the annealing effect of subsequent weld passes. However the grain structures of regions where no pass overlapping occurred (See figures 29 and 32) were very similar to those of single pass underwater welds even though hardness readings were significantly lower.

C5. 3/4" HY-80 Tee Joints.

The minimum preheat temperature for 3/4" HY-80 plate is 125°F verses 75°F for ¼" plate , therefore the adverse effect of ambient water temperature on the underwater weldability of 3/4" HY-80 was expected to be considerable. Experimental results and metallographic examination of 3/4" welded joints confirmed this expectation.

Underwater Bend Strength. Bend tests of 3/4" underwater welded multipass tee joints were conducted for the purpose of comparing tee tend performance to base plate performance. However the bend strength of the unwelded 3/4" plate greatly exceeded the rated capacity of the bend testing machine resulting in an incomplete set of data. Even so some tentative conclusions on the relative bend strength of 3/4" tee joints can be drawn. Firstly as shown in Table 6B the

bend strength of these joints is well below 58% of base plate bend strength compared to 68.4% for ½" tee joints. Secondly the ratio of total bend angle at failure for 3/4" tee joints is 24.5% the total bend angle of ½" tee joints. Assuming 3/4" base plate has the ductility of ½" base plate (i.e. 180° total bend angle without failure), the percentage of 3/4" tee joint to base plate ductility is only about 5%.

Underwater Weld Shear Strength. Tee-tensile test results were equally disappointing. The shear strength of 3/4" underwater welded multipass tee-joints was only 31.4% the shear strength of ½" underwater welded multipass tee joints. The loss in weldability of thick HY-80 plate (>½") is extraordinary.

Metallographic Examination. Since the severity of surface defects (i.e. undercut and surface cavities) was comparable to that of ½" underwater welds, the great loss in overall weld quality must be attributed to internal weld defects and degradation of weld zone microstructure. Metallographic analysis showed that internal weld defects caused most of the loss in joint strength and ductility.

Figure 35 shows a crossection of a 3/4" underwater welded tee joint (the right hand fillet has one less pass than the left hand fillet). Three weld defects are immediately obvious;

a. large regions of slag entrapment in the vicinity of the weld roots.

b. lack of fusion in the vicinity of the weld roots.

c. lack of penetration at the weld roots due to premature weld metal solidification.

Even with higher heat inputs the first pass on each side of the tee was unsuccessful in penetrating the bottom tip of the bevel. Even though a relatively thin 1/8" diameter electrode was used to make the weld, the electrode was still too large to reach all the way to the tip of the bevel, and so weld metal had to be "blown into" the groove by the arc forces. Entrapped water could have solidified the weld metal droplets as they approached the bevel root resulting in lack of fusion and slag entrapment. Figures 36 through 38 show that slag entrapment, porosity, and poor fusion occurred simultaneously in many regions resulting in extremely poor joint strength.

Figure 34 shows Vickers hardness through 3/4" specimen weld zones in order to correlate grain structure to hardness. The maximum hardness of both the 1/4" and 3/4" welds occurs in the center of the multipass zones. However the maximum hardness of the 3/4" multipass tee joints is significantly greater than that of the ¼" multipass lapweld. An increase of 67% in minimum preheat temperature resulted in a 30% increase in maximum hardness in the 3/4" specimens compared to the ¼" specimens. Thus the ambient temperature and quenching effect of the water environment drastically alters the 3/4" joint multipass zone hardness.

C6. $\frac{1}{2}$" and 3/4" HY-80 Tee Joints Welded in Salt Water

As a last step in this investigation $\frac{1}{2}$" and 3/4" tee joints were welded in salt water, to see if there was any difference in joint weldability between fresh and salt water. "Dayno Synthetic Sea Salt" (See appendix B) was used to make the artificial sea water used in this test. Since time did not permit the cutting and testing of test specimens, it was decided to weld the two sets of tee joints under the identical conditions used in making the fresh water welds and then make a qualitative comparison of weld quality obtained in the two aqueous media. No reference was found which investigated the difference in the hydrogen cracking potential of a salt water media compared to fresh water, however since no case of hydrogen induced macrocracking was observed in any fresh water weld, non was anticipated in salt water welding. The rationale here was that fresh water welding produced an ample supply of dissociated hydrogen in the arc, and quenched the weld bead just as fast as salt water would. Thus the conditions for hydrogen cracking were present, and the fact that none occurred in fresh water was quite surprising. Salt water welding would be expected to cause some changes in the rate of hydrogen dissociation, and possibly in the amount entrapped in the weld zone, but these would be minor perturbations from fresh water welding conditions, and therefore no major changes from fresh water results would be expected.

Section D - Conclusions and Recommendations on the Underwater Welding of HY-80 Steel

D1. Conclusions

a. The U.S. Navy is increasingly using HY-80 steel in the fabrication of surface ship hulls. This is the time to begin developing an efficient operational system for the underwater repair and salvaging of HY-80 steel hulls. This investigation studied the feasibility of welding HY-80 plate underwater using current air welding technology. Experimental results showed that fairly efficient joints, comparable to underwater welded mild steel joint efficiency, could be fabricated underwater with thin HY-80 steel plate. (Thin plate here means $\leq \frac{1}{2}$", i.e. where minimum preheat temperature increases above 75^{o}F). For thicknesses greater than $\frac{1}{2}$" underwater weldability decreases dramatically.

These findings may appear restrictive however, due to the higher strength to weight ratio of HY-80 steel compared to mild steel, most unarmored naval ship hulls will require relatively thin plate when fabricated from HY-80 steel. Therefore the $\frac{1}{2}$" maximum thickness restriction may in fact encompass the large majority of future naval ship hulls.

b. Loss in underwater welded joint strength and ductility,

when compared to similar air welded joints, resulted from two main causes; weld undercut, and weld zone microstructural changes and defects caused by severe quenching. It was found that for ¼" HY-80 steel plate undercut accounts for almost 75% of the total underwater weld degradation, and weld zone structural changes and effects for the other 25%.

c. In 3/4" HY-80 underwater welded joints, internal weld defects, especially heavy slag inclusion, prevented adequate fusion of weld metal and base metal. This accounts for the major portion of total weld degradation when compared to 3/4" HY-80 base plate.

d. In general, multipass underwater welding of HY-80 steel is preferred to single pass welding. Multipass welds were much more porous than single pass welds, but the effect of porosity was secondary compared to single pass weld undercut caused by the severe quenching of the aqueous environment. Porosity will reduce effective weld crossectional area, but undercut will cause severe stress intensities at the notch roots which in turn will cause premature, catastropic fracture especially in the presence of bend stresses.

Multipass welds not only decrease the degree of undercut but increase fillet size and in so doing "push" the undercut further away from the joint intersection.

Therefore a crack which initiates at an undercut notch root must propagate through a greater portion of the fracture tough HY-80 base plate rather than through the more notch sensitive weld metal and heat affected zone.

e. It was demonstrated in the underwater welding of thin HY-80 plate that weld undercut could be greatly reduced (but not eliminated) through the optimization of welding parameters and proper welding technique. This is where the largest payoff per dollar invested will result.

f. Underwater weld quality and overall joint strength could be significantly increased through the use of post weld surface treatment. After both single and multipass welding, weld beads should be mechanically peened or ground down in order to eliminate surface cavities, and reduce or eliminate undercut.

Unlike weld undercut, surface cavities will not significantly reduce joint strength per se, however it will allow the water environment access deep into the weld metal. This will result in accelerated corrosion through the formation of differential aeration cells which would eventually cause extensive local corrosion through the heat affected zone and into the base metal.

D2. Recommendations

a. Shrouded underwater welding of HY-80 steel should be tested and, if proven satisfactory, further developed. Welding shrouds have been used with good success in the underwater welding of mild steel.[11] Their main influence was to reduce the severe quenching effect of the underwater environment and provide some joint preheating upstream from the arc. Since excessive quenching has a more adverse effect on the underwater welding of high strength steels than on mild steels, the resultant weld quality should be proportionately higher. The preheating effect could be extremely beneficial in the underwater welding of thick HY-80 steel plate.

b. Underwater welding of HY-80 steel should be studied at greater depths, to obtain a more realistic appraisal of the weld quality and joint strength that could actually be achieved at operational welding depths.

c. The effects of welding parameters and welding technique on the degree of weld undercut in single and multipass underwater welds should be studied further.

d. The effects of input welding parameters on the hydrogen content of single and multipass welds should be studied with the goal of minimizing entrapped hydrogen (and other gases).

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[11] Silva op. cit. pp 75-112

e. Efficient and safe methods of preheating and postheating joints underwater, in addition to shrouding, should be studied.

f. Underwater welding of HY-80 steel can be accomplished with present SMA underwater welding equipment. however an extensive training program is needed now to train and qualify divers in the underwater welding of HY-80. Also special tooling for post-weld peening, grinding, etc. may have to be developed if presently available pneumatic and electrical hand-held tooling is not adaptable to underwater work.

APPENDIX A

SAMPLE CALCULATIONS

1. Shear Strength.

$$\text{Shear Strength/Linear Inch} = \frac{\text{Maximum Load to Failure(lb)}}{\text{2x Specimen Width (in)}}$$

$$\text{Shear Strength (psi)} = \frac{\text{Shear Strength}}{\text{Linear Inch}} \times \frac{1}{\text{Ave Throat Dimen.(in)}}$$

Example: Max Load to Failure = 10,000lb

Specimen Width = $1\frac{1}{4}$"

Ave Throat Dimen. = 0.20"

$$\text{Shear Strength/Linear Inch} = \frac{10,000\text{lb}}{2\text{x } 1.25} = 4,000\text{lb/in}$$

$$\text{Shear Strength} = 4,000\text{lb/in} \times \frac{1}{0.20"} = 20,000 \text{ psi}$$

2. Heat Input.

$$\text{Heat Input} = \frac{\text{Current (AMP) x Voltage(V)}}{\text{Travel Speed (in/min)}} \times \frac{60\text{sec}}{\text{min}} = \text{Joules/in}$$

Example: Current = 210 AMP (DC)

Voltage = 28 VOLT

Travel Speed = 11.5 in./min.

$$\text{Heat Input} = \frac{210\text{A x } 28\text{V}}{11.5\text{in/min}} \times \frac{60\text{sec}}{\text{min.}} = 30,678 \text{ joules/in.}$$

From MIL-S-16216H:

Max. Heat Input = 45,000 joules/in for the thickness $\leq \frac{1}{2}$"

= 55,000 joules/in for thickness $> \frac{1}{2}$"

APPENDIX B

SYNTHETIC SEA WATER COMPOSITION

Formula for one liter of solution at 1.025 specific gravity:

Compound	Weight(mg)	Compound	Weight(mg)
$NaCl$	27,553.0000	$LiCl$	0.9906
$MgCl \cdot 6H_2O$	5,800.0000	$Ca(C_6H_{11}O_7)_2$	0.6604
$MgSO_4$	6,921.0000	KI	0.0951
$CaCl_2$	1,379.6000	KBr	28.5370
KCl	733.9000	Cu as chloride	0.0018
$NaHCO_3$	209.7000	Al as sulphate	0.0082
$SrCl_2 \cdot 6H_2O$	19.8130	Co as sulphate	0.0201
$MnSO_4 \cdot H_2O$	3.9626	Rb as sulphate	0.1120
$Na_2HPO_4 \cdot 7H_2O$	3.3021	Zn as sulphate	0.0159
$Na_2MoO_4 \cdot 2H_2O$	0.9906	Fe as sulphate	0.0233

Dayno Synthetic Sea Salt
Dayno Sales Co.
Lynn, Massachusetts

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